LEIDSE GEOLOGISCHE MEDEDELINGEN, Deel 51, Aflevering 1, pp. 49–55, 24–5–1977

THE DEVELOPMENT OF MICROTEXTURES AND DISLOCATION SUBSTRUCTURES IN NATURALLY DEFORMED OLIVINES FROM VARIOUS GEOLOGICAL ENVIRONMENTS

BY

J. M. A. BUISKOOL TOXOPEUS[1])

ABSTRACT

High voltage electron microscopy and petrofabric analysis techniques are used to distinguish dislocation substructures and preferred orientation patterns of the mineral olivine in naturally deformed peridotites. In order to obtain information over a wide field in which different types of deformation occur, samples were studied from various geological environments. Olivines from lherzolite nodules in basalts (Dreiser Weiher, Germany; Auvergne, France), alpine-type orogenic peridotites (Finero, Alpe Arami, Switzerland; Kittelfjäll, Sweden), and peridotite nodules in kimberlites (Lesotho) show crystal plasticity as an important mechanism allowing deformation. Depending on the intensity and conditions of deformation (P, T, $\dot{\varepsilon}$), various glide systems and dislocation substructures are developed. Increasing deformation produced dislocation substructures in which complete sequences are recognized from strain hardening regimes via (dynamic) recovery up to different types of recrystallization. Depending on the deformation conditions, dislocation glide systems {0kl} [100] were produced during high temperature and/or low strain rate creep, while at lower temperatures and/or higher strain rates, dislocations with Burgers vector **b**=[001] predominate. This makes it possible to distinguish between mono- and poly-phase deformation influences in the dislocation substructures in some orogenic peridotites and kimberlite nodules. Literature results of experimental deformation on olivine, and detailed information about the structural-petrological history of the studied rocks are indispensable and therefore extensively discussed.

SAMENVATTING

Hoog voltage elektronenmicroscopie en maakselanalyse zijn gebruikt om dislokatiesubstrukturen en voorkeursorientatie patronen van kristalassen te onderkennen van het mineraal olivijn in natuurlijk gedeformeerde peridotieten. Ten einde informatie over een zo breed mogelijk gebied te verkrijgen waarin verschillende deformatietypen voorkomen, zijn monsters bestudeerd die gedeformeerd zijn onder verschillende geologische omstandigheden. Olivijnen van lherzolietinsluitsels in bazalten (Dreiser Weiher, W. Duitsland; Auvergne, Frankrijk), alpino-type orogene peridotieten (Finero, Alpe Arami, Zwitserland; Kittelfjäll, Zweden), en peridotietinsluitsels in kimberlieten (Lesotho) tonen dat plastische vervorming van kristallen een belangrijk deformatiemechanisme is. Afhankelijk van de sterkte en de omstandigheden (P, T, $\dot{\varepsilon}$) waaronder vervorming plaatsvond, hebben zich verschillende slipsystemen en dislokatiesubstrukturen ontwikkeld. Toenemende deformatie vormde dislokatiesubstrukturen waarin volledige opeenvolgingen zijn waargenomen vanaf 'strain hardening' via (dynamische) recovery tot en met verscheidene typen van rekristallisatie. Afhankelijk van de deformatieomstandigheden worden {0kl} [100] dislokatieslipsystemen gevormd tijdens hoge temperatuur en/of lage strain rate creep, terwijl bij lagere temperaturen en/of hogere strain rates, dislokaties met Burgers vector **b**=[001] overheersen. Hierdoor is het mogelijk om een onderscheid te maken tussen enkelvoudige en meervoudige deformatieinvloeden in de dislokatiesubstrukturen in enkele orogene peridotieten en insluitsels in kimberlieten. Literatuurresultaten over experimentele deformatie van olivijn en nauwkeurige informatie over de struktureel-petrologische geschiedenis van de bestudeerde gesteenten zijn onmisbaar in dit onderzoek en worden daarom uitgebreid besproken.

CONTENTS

CHAPTER I

INTRODUCTION

Since olivine, $(Mg, Fe)_2SiO_4$, is the subject of profound interest because of its possible upper mantle origin, numerous studies have been carried out, investigating the experimental and natural deformation behaviour of this mineral. In this way, flow processes in the upper mantle have been studied together with possible modifications of the original substructures by subsequent annealing or lower

1) Geologisch en Mineralogisch Instituut der Rijksuniversiteit, Garenmarkt 1b, Leiden, The Netherlands.

temperature deformation processes in a crustal environment. Some years ago, these studies were mainly based on optical microscopy techniques, discussing (micro-) structures and petrofabric analysis. Recently, however, a new technique, high voltage transmission electron microscopy, became applicable to minerals. Since that period more fundamental research became possible on the intracrystalline deformation features, revealing relations between dislocation substructures and deformation/recrystallization processes. Pressure (P), temperature (T), and strain rate ($\dot{\varepsilon}$) fields in which various slip systems were dominant could be determined more accurately (Raleigh, 1968; Carter & Avé Lallemant, 1970; Green & Radcliffe, 1972; Phakey et al., 1972; Green, 1976; and many others).

Although electron microscopy, especially on experimentally deformed olivine crystals, has been performed by many workers, comparatively little work has been carried out so far on naturally deformed olivine-rich rocks.

The papers submitted here as a dissertation, concern various aspects of naturally deformed olivine-bearing rocks, studied with both electron microscopy and optical microscopy techniques. The sequence in which the papers are arranged gives the order of development of this research and the preparation of the manuscripts.

The starting point of this work in 1972 was the renewed investigation of the chlorite peridotite mylonite of Alpe Arami (Switzerland), studied by J. R. Möckel (1969), which exhibits two essentially different preferred orientations (Buiskool Toxopeus, 1976; Buiskool Toxopeus, 1977). These two fabrics were related to two groups of grains, to wit: larger, strained crystals (porphyroclasts) and smaller, recrystallized matrix grains. The optical microscope used for the petrofabric analysis and the study of microtextural development, however, was not able to solve the more fundamental problems that presented themselves, for instance how the supposed intracrystalline deformation mechanisms operated, which of the slip systems predominated, and how recovery and recrystallization processes took place. Therefore the scope of the study was extended by electron microscope work, giving an insight into the dislocation substructures, and as a result, a hypothetical model of the dislocation deformation mechanisms was proposed (Buiskool Toxopeus, 1976). A third phase in this investigation was the comparison of the electron microscope results from the Alpe Arami mylonite with a wider range of olivine-bearing rocks, collected from various geological environments, in order to obtain more diverse data about the relation of the dislocation deformation mechanisms and the conditions under which they were activated (Buiskool Toxopeus & Boland, 1976; Boland & Buiskool Toxopeus, 1977). For this reason, olivine-rich rocks were studied from essentially different categories as xenoliths transported directly from the upper mantle or lower crust in alkaline basalts, or kimberlites such as:

1. undeformed (Dreiser Weiher, Germany) to weakly deformed (Auvergne, France) lherzolite nodules in lavas;
2. moderately deformed peridotite nodules in kimberlites (Lesotho).

This diversification in studied samples resulted in comparatively simple models for a progressive single phase deformation under various conditions. The fourth and last phase of this work was to switch back to the highly deformed metamorphic peridotites (and some kimberlites), which were tectonically emplaced in their present position, exhibiting a complicated deformation history. In this way a better insight was achieved in polyphase deformation and recrystallization processes under various metamorphic regimes. The influence of these processes on the dislocation substructures was determined (Buiskool Toxopeus, 1977a; Calon & Buiskool Toxopeus, 1977). Moderately to highly deformed orogenic peridotites were studied such as the phlogopite peridotite at Finero (Switzerland) and the garnet peridotite at Alpe Arami (Switzerland). In cooperation with T. J. Calon the peridotite at Kittelfjäll (Sweden) was studied for this purpose as regards its structural petrology (Calon, in press) and the influence of its complicated history on the dislocation substructure (Buiskool Toxopeus, 1977a; Calon & Buiskool Toxopeus, 1977). In this final phase of research, a new dislocation decoration technique has been applied, producing optically visible dislocations in thin sections (Kohlstedt et al., 1976).

CHAPTER II

DISCUSSION OF THE RESULTS AND CONCLUSIONS

Rather than to repeat the subject matter contained in the papers, a review of the results and conclusions of these individual papers is deemed more appropriate, in order to produce a philosophical link between the papers, and to get an overall impression of the work performed.

Although the olivine-bearing rocks were studied only with electron microscopy, and in some cases with petrofabric analysis techniques, it was possible to correlate these results with the deformation and metamorphic histories the rocks have undergone. Especially the relationship between observed dislocation substructures and conditions of deformation needs careful consideration, because these arrangements may have been produced either by the last deformational event only, or by several events recorded in the dislocation arrangement. Therefore this review starts with the simple olivine dislocation substructures in the lherzolite nodules, after which more complicated substructures in nodules in kimberlites and orogenic peridotites will be discussed. This sequence will also show the transformations of the dislocation substructures, as a consequence of one single, progressing deformation phase, into complicated polyphase deformation arrangements.

NON-OROGENIC PERIDOTITES

The studied lherzolite nodules from Dreiser Weiher and Auvergne defined dislocation arrangements pointing to an undeformed to weakly deformed character of the material (Buiskool Toxopeus & Boland, 1976). The most significant results justifying this conclusion are:

1. the configuration of the (100) arrays of **b**=[100] edge dislocations, with large, irregular mutual spacings;
2. the low individual dislocation density, especially the few **b**=[001] dislocations;
3. the large prismatic loops (Ø 10 um).

Within this development of dislocation arrangements, progressive deformation features from undeformed to weakly deformed could be recognized, exhibiting smaller spacings between the (100) arrays, the appearance of some slip planes and twist boundaries, a beginning development of bowing out phenomena, and generally higher dislocation densities.

As discussed (Buiskool Toxopeus & Boland, 1976), this arrangement indicates mainly activity of the {0k1} [100] slip systems. In general, the olivine shows strong recovery features in that only (100) arrays of dislocations were present, and no slip planes, except some individual dislocations, were left. The large loops also point to the activity of diffusional processes. Summarizing the fabric work on lherzolite nodules, it can be concluded (Collée, 1962; den Tex, 1969) that the nodules possess weak host-rock effusion deformation features, resulting in creep or recovery that indicates activity of the {0k1} [100] slip systems only. The latter feature is in agreement with observations of Carter & Avé Lallemant (1970), Avé Lallemant & Carter (1970), Green & Radcliffe (1972), and many others, all suggesting high temperature, low strain rate conditions, characteristic of the upper mantle deformation regimes, from which the nodules may have been derived. In the studied samples no evidence was found to suggest overprinting by subsequent deformation events. The dislocation arrangement in these high temperature nodules shows extensive activity of diffusional processes. Therefore, the recovery in the dislocation arrangement observed here, should have a more static character than the dynamic recovery implied in the orogenic peridotites.

OROGENIC PERIDOTITES

The work on the orogenic peridotites (Alpe Arami, Finero, Kittelfjäll) was divided into two parts: (i) petrofabric analysis and (ii) electron microscopy.

The petrofabric analysis (Buiskool Toxopeus, 1976, 1977) was carried out to understand the fabrics analysed by J. R. Möckel (1969) in the Alpe Arami chlorite peridotite mylonite, showing a γ_{ol}=[100] fabric for the strained porphyroclasts, and an α_{ol}=[010] fabric for the recrystallized matrix grains. The main problem was the γ_{ol}=[100] preferred orientation normal to the foliation plane in the mylonite. This orientation makes it impossible to assume that plastic deformation on the slip system {0k1} [100], which was deduced from optical and electron microscope observations, has oriented the porphyroclasts in this position during the generation of the mylonite. Petrofabric analysis and especially axial distribution analysis on small, defined areas, however, explain that both porphyroclasts and matrix grains rotated towards the α_{ol}=[010] fabric position, a rotationally stable end orientation for activated slip on {0k1} [100]. The amount of rotation towards the α_{ol}=[010] fabric is connected to the amount of strain undergone. A complete gradation from γ_{ol}=[100] to α_{ol}=[010] fabrics has been identified in specific microstructures related to increasing strain in those areas. The γ_{ol}=[100] fabric in some of the porphyroclasts is believed to represent a rotationally unstable end orientation under the deformation conditions present in the mylonite. This fabric was inherited from the neighbouring chlorite peridotite, and still exists because it was preserved from recrystallization by this orientation unfavourable for deformation.

Electron microscope observations from the Alpe Arami mylonite (Buiskool Toxopeus, 1976, 1977, 1977a; Buiskool Toxopeus & Boland, 1976) support the conclusions based on the petrofabric work. Compared with the electron microscope results from the undeformed to weakly deformed lherzolite nodules from basalts, moderate deformation features were recognized both in porphyroclasts and matrix grains of the Alpe Arami material.

In the porphyroclasts, regularly and closely spaced (100) arrays, some slip planes defining {0k1} [100] systems, and moderate densities of **b**=[100] dislocations predominating over **b**=[001] dislocations, were suggested to resemble those found in metallic and ceramic systems undergoing dynamic recovery. It can be concluded that dynamic recovery has been operative in the porphyroclasts, resulting in a dynamically stable but not static substructure.

In contrast to the porphyroclasts, the matrix was accommodating most of the strain in the rock. This feature is indicated by a small subgrain size, a higher individual dislocation density, less well developed (100) arrays with larger mutual spacings, and a higher density of slip planes. Dynamic recrystallization is suggested to have occurred in the matrix, developing small dislocation free new grains. In this cyclical process, the dynamic recovery was still present, giving rise to some analogy with the dislocation substructure in the porphyroclasts. Apart from the above-mentioned differences in dislocation substructure between the porphyroclasts and the matrix grains, some bands of individual dislocations with **b**=[001] are present in the matrix grains. It should be noted, however, that the quantity of these **b**=[001] dislocations is less (Buiskool Toxopeus, 1977a) than suggested in a previous publication (Buiskool Toxopeus, 1976). Although the density of **b**=[001] dislocations within the bands is rather high ($5\times10^8/cm^2$), within the subgrains generally few **b**=[001]

dislocations occur, with densities in the range of 10^6 to $10^7/cm^2$.

From experimental data on olivine deformation (e. g. Carter & Avé Lallemant, 1970; Green & Radcliffe, 1972; Blacic & Christie, 1973) it is established that slip in the [001] direction in olivine, caused by this type of dislocations, dominates at high strain rates and/or low temperatures. From geological evidence, however, it is unlikely that the mylonite has undergone two deformation phases, with one phase causing the [100] slip, and the other phase causing the [001] slip. It appears more likely that only one deformation phase generated the mylonite, initially under high temperature/low strain rate conditions, creating mainly [100] slip systems, and that subsequent stages in the same deformation phase, probably under decreasing temperature conditions, created some [001] dislocations. The slight influence of this later stage explains the few **b**=[001] dislocations developed; inhomogeneously distributed strain only created some [001] dislocation bands. Since the argument for two types of dislocations is later used for the presence of two separate deformation phases (Buiskool Toxopeus, 1977a; Boland & Buiskool Toxopeus, 1977), one should realize that the [001] dislocations in Alpe Arami are restricted to specific bands only, while in the polyphase deformed rocks the [001] dislocations always define complicated arrangements.

Electron microscopy was carried out on the phlogopite peridotite of Finero (Buiskool Toxopeus & Boland, 1976), for comparison with the Alpe Arami mylonite. Although the geology of the body was not investigated by the author, and electron microscope results were based only on a few rock samples, some conclusions could be drawn based on the results from other peridotites. In the Finero peridotite the dislocation arrangement of the (100) arrays resembles to a certain extent the arrangement in the other peridotites studied (Alpe Arami, Kittelfjäll), indicating slip in the [100] direction with an important amount of dynamic recovery. Apart from this, the arrangement of numerous **b**=[001] dislocations with an excessive amount of small, prismatic loops, **b**=[001], provides evidence for dislocation generation and interaction processes. As already mentioned, the difference in conditions for activating slip in the [100] and [001] directions suggests that this arrangement has resulted from polyphase deformation. Especially the arrangement of curved **b**=[001] dislocations, forming dipoles and loops in distinct zones in the deformed olivine crystals, appears to have originated from an additional deformation phase under different conditions, overprinting a previous high temperature, low strain rate creep structure.

The overall dislocation substructure in the Finero peridotite deviates from the Alpe Arami mylonite, in that during a second deformation phase, **b**=[001] dislocations have been generated extensively, forming interactions and slip structures. Although this feature is also recorded from the Kittelfjäll peridotite (Buiskool Toxopeus, 1977a; Calon & Buiskool Toxopeus, 1977), the [001] dislocations in the Finero peridotite form higher densities with more interaction features (loops). It can be concluded that moderate first phase deformation/recovery features in Finero are present, comparable with [100] dislocation substructures in Alpe Arami and Kittelfjäll, formed under possibly similar high temperature creep deformation conditions. Although in the Finero material the features of a second deformation phase indicate generally lower temperatures and/or higher strain rate conditions, the developed substructures (and micro-structures) are not similar to second phase substructures in the Kittelfjäll peridotite. Therefore, these two second phases must have occurred under completely different conditions within the low temperature and/or high strain rate regime.

In the Kittelfjäll peridotite the supposed effects on the dislocation arrangement, caused by polyphase deformation, have been studied in more detail (Buiskool Toxopeus, 1977a; Calon & Buiskool Toxopeus, 1977). For this purpose, samples have been selected, and mutually compared, from mono- and poly-phase deformed microstructures under decreasing metamorphic conditions.

Single phase deformation observed in Kittelfjäll (first deformation phase - foam structure or microstructure I) and in Alpe Arami under high temperature (at least greater than 650°C) and low strain rate conditions, resulted in both rocks in similar dynamic recovery features in the porphyroclasts. The substructure is mainly defined by moderate densities of **b**=[100] dislocations, by regularly and closely spaced (100) edge dislocation arrays with **b**=[100], and by some slip planes, forming a subgrain structure of simple dislocation walls. In general there are few **b**=[001] dislocations, pointing to {0k1} [100] as the main operative slip system under these high temperature, low strain rate conditions. During this first deformation phase in the Kittelfjäll peridotite, recrystallization occurred, forming foam structured matrix grains (Ø 0.5–2 mm). Some very small grains (several um), hardly visible with the optical microscope, have been developed during the minor second phase overprinting the foam structure. Electron microscopy has revealed three types of subgrains, which are based on internal dislocation substructures, that have developed within the foam-structured matrix grains. The first type of subgrain has originated from the first deformation phase, while the other two types were developed during increasing second phase deformation, resulting in some nucleation recrystallization (subgrain type III).

The subgrains in the matrix of the Kittelfjäll peridotite, which resulted from the first phase, resemble the substructure in the Alpe Arami matrix grains, in that the (100) arrays were irregularly and widely spaced, together with an increase in the number of cross arrays (slip planes). The recrystallization process that developed this subgrain type is argued to be a polygonization process that rotated the subgrain out of the porphyroclast orientation during the first deformation phase. The olivine subgrains, or clusters of subgrains, have continuously increased their misorientation with increasing strain, and eventually appear in optical micrographs as individual foam-structured matrix grains, surrounded by high angle boundaries, in the same way as described for quartz recrystallization (White, in press).

In some areas in the Kittelfjäll peridotite, the second phase has hardly been developed at all (foam structure), but in localized shear zones at the rim of the body, this phase was intense, giving rise to a new microstructure (mortar structure or microstructure II). This second phase was developed under lower metamorphic conditions than the first phase: upper greenschist–lower amphibolite facies, with maximum temperatures of 550°C, and high strain rates.

Porphyroclasts, highly deformed by intense shear, are surrounded by smaller, deformed matrix grains (Ø 1–5 mm) related to the above-mentioned foam structure, and by abundant very fine-grained (Ø 1–200 um) matrix grains (mortar). The porphyroclasts show high dislocation densities and strong bowing out of dislocations from (100) arrays into (001), defining subgrains parallel to [010], and causing a high shear strain situation in these crystals (single set of parallel screw dislocations). Therefore initial dynamic recrystallization, in the form of nucleation within the clasts, has started along defined planes such as (100), (001), (010), forming new strain free nuclei.

The matrix grains again define the same three types of subgrains. The first type resembles the subgrains in the foam-structured matrix grains, developed during the first deformation phase, and is argued to have originated from this phase. This subgrain type (I) thus escaped the influence of the second deformation phase in microstructure II to a large extent, and was developed only in the smaller matrix grains (Ø 1–5 mm).

The second type of subgrain (II) was developed out of the type I subgrains during the increasing second deformation phase. The dislocation arrangement is complicated with poorly developed (100) arrays, with an increasing number of cross arrays (slip planes), and with high individual dislocation densities with strongly curved dislocations and loops. Individual dislocations with **b**=[001] are predominant over **b**=[100] dislocations. It was concluded that both subgrain types I and II represent original foam-structured matrix grains, progressively deformed in microstructure II under conditions of the second deformation phase.

The third subgrain type (III) represents dislocation free nuclei in an initial recrystallization phase, forming very small mortar grains.

A comparison between the two deformation phases and their different conditions on the one hand, and the microstructures with their various dislocation arrangements caused by these phases on the other hand, resulted in the following conclusions:

A. Deformation under high temperatures (>650°C) and low strain rate conditions resulted in extensive dynamic recovery in the porphyroclasts and polygonization recrystallization, causing foam structures in the matrix grains. The operative slip system was mainly {0kl} [100].

B. Deformation under lower temperatures (<550°C) and higher strain rates resulted in dislocation substructures in which extensive glide occurred, with dislocation generation and interaction features, with less dynamic recovery features, but with initial recrystallization in the porphyroclasts and matrix grains. Recrystallization took place mainly in the most strongly deformed regions by nucleation, forming mortar type matrix grains. Important operative slip systems were the (100) [001], (010) [001], and (110) [001] systems in addition to {0kl} [100].

The large differences in microstructures as well as in dislocation substructures were developed not only by the temperature differences (only 100°C as a minimum difference between 650°C and 550°C) controlling the diffusional processes in the rock, but strain rate conditions must also have been of major importance. Therefore, the various results of the deformation phases can be explained by the important interplay between temperature and strain rate during natural deformation.

The orogenic peridotites (Finero, Alpe Arami, Kittelfjäll) generally show polyphase deformation features, resulting in several microstructures and dislocation substructures. In some cases, overprinting of subsequent dislocation substructures is present, and to some extent original substructures could be reconstructed. It should be kept in mind, however, that the orogenic peridotites were generally exposed to a large number of deformation events, under often high temperatures, in their crustal deformation history. Therefore, it seems highly speculative to interpret the electron microscope results in these orogenic rocks in terms of upper mantle flow. Crustal deformation conditions, however, can be excellently described and assessed by the observed dislocation arrangements.

KIMBERLITE NODULES

As a last example of olivine dislocation substructures, electron microscopy was carried out on coarse-grained peridotite nodules from some kimberlites (Boland & Buiskool Toxopeus, 1977). The results again indicate that the olivines have been subjected to variable deformation conditions.

An early deformation phase was recognized in the ordered substructural (100) arrays, slip planes and low densities of **b**=[100] dislocations, pointing to activity of {0kl} [100] slip systems during high temperature creep conditions. Apart from this substructure, **b**=[001] dislocations are present in cellular arrangements or as high densities of individual dislocations with diverse geometries such as loops, helices, dipoles or other strongly curved forms. The pronounced activity of **b**=[001] dislocations again indicates a phase or condition of deformation, different from that required to produce the high temperature creep type structures of the **b**=[100] dislocations.

The coarse-grained kimberlite nodules show a close similarity with the orogenic, polyphase deformed, alpine-type peridotites, especially the phlogopite peridotite from Finero. Therefore, electron microscopy is suggestive of a deformation history in two phases under different conditions for these peridotite nodules. Initially, high temperature creep in the upper mantle with low strain rate conditions activated the {0kl} [100] slip systems. Subsequently the nodules have been deformed at higher strain rates and lower temperatures, activating the [001] dislocations. This second phase overprinted the creep structures and is argued to have occurred during the emplacement of the material in its present position.

From the beginning of this project I was very fortunate to find Dr. J. N. Boland and Drs. T. J. Calon interested in olivine, and perhaps it is the place here to indicate their contributions to my work.

As a skilful electron microscopist Dr. Boland was already working on olivine (Boland et al., 1971) when I contacted him in 1972 for this project. I was very fortunate to find Dr. Boland prepared to introduce me into high voltage electron microscopy in Oxford for half a year. During that period he had great influence on me, mainly pointing to the physical aspects of dislocations and their various substructures. Especially the contrast analysis for Burgers vector determinations were carried out under his guidance (Boland, 1976). Our work in Oxford resulted in a joint paper (Buiskool Toxopeus & Boland, 1976). Although the experimental work was carried out by me, Dr. Boland contributed largely to the ultimate result by indicating the various possibilities of dislocation processes during deformation, forming the present dislocation substructures.

After our joint period in Oxford we kept in regular contacts by letter exchange. Our individual experiments in Canberra and Oxford resulted in a second joint paper (Boland & Buiskool Toxopeus, 1977) about peridotite nodules in kimberlites. In this paper Dr. Boland is responsible for the geochemical data and the connection of these data with electron microscope results. My contribution to this work was the electron microscopy of one of the nodules, and the recognition of some parallelism in dislocation substructure with the arrangements in orogenic peridotites, suggesting a complex deformation history.

Apart from these papers I have discussed most of my other results with Dr. Boland and great resemblance was recognized between the orogenic peridotites I have studied, and the Anita Bay peridotite he is working on.

The contribution of Drs. Calon (Buiskool Toxopeus, 1977a; Calon & Buiskool Toxopeus, 1977) consisted of the supply of geological information and samples from the Kittelfjäll peridotite. Drs. Calon has developed the model for the deformational and metamorphic history, by making an extensive structural petrological study of this peridotite body (Calon, in press). The electron microscope results which I have compiled (Buiskool Toxopeus, 1977a) fit extremely well within his structural frame work. This made it possible for us to have a mutual check on our researches, and to pin down the structural and metamorphic events within more precise limits.

Some concluding remarks should be made about the use of electron microscopy in determining the history and conditions of deformation of minerals.

Transmission electron microscopy, especially at high voltages, is a very powerful tool to obtain an insight in the intracrystalline deformation mechanisms. However, without the knowledge of geological field observations that give parameters for the number of deformation phases and their metamorphic environments, this investigation would have lost indispensable aspects. Experimental studies should also be used to support the determination of natural deformation conditions and history. Therefore electron microscopy should be used together with all other relevant techniques in order to make it the most profitable source of reliable information.

ACKNOWLEDGEMENTS

Under the supervision of Professor Dr. E. den Tex, a research project in the Department of Petrology, Mineralogy and Crystallography of the Geological Institute, University of Leiden, already resulted in several detailed investigations in olivine bearing rocks (Collée, 1962; Avé Lallemant, 1967; Möckel, 1969). The knowledge and experience of these investigations were indispensable for this research.

The author is greatly indebted to Professor den Tex for proposing the subject for this investigation, and for allowing me much freedom to pursue various aspects of it. His vast knowledge of petrofabrics, and his critical reading of all the manuscripts were a great support.

I am especially thankful to Dr. J. N. Boland for his advice and for the many discussions on electron microscopy, and to Drs. T. J. Calon for the supply of many data from his work on the Kittelfjäll peridotite, and the cooperation that resulted from our combined efforts.

The author wishes to thank Professor Sir Peter Hirsch for the use of the HVEM facilities at the Department of Metallurgy and Science of Materials, Oxford University, England.

I am particularly indebted to Professor Dr. P. Hartman and to Dr. G. S. Lister for their encouragement and advice during the preparation of this study. I am grateful to Dr. A. T. Senior for correcting the English manuscript.

Without the cooperation of the entire staff of the Geological Institute, this study would not have been possible. I want to thank especially Mr. F. Schild; Mrs. E. M. Prins-van der Drift; Mr. H. B. van der Meer for the library facilities; Messrs. M. Deyn, H. C. de Graaff, C. J. van Leeuwen and J. Schuilenburg for the preparation of the excellent thin sections; Messrs. W. C. Laurijssen and W. A. M. Devilée for the photographical work; and Mr. J. Bult together with Messrs. M. L. Brittijn, K. A. Hakkert and B. G. Henning for the preparation of the drawings.

Grants from the 'Stichting Molengraaff-Fonds' at Delft, and from the Netherlands Organization for the Advancement of Pure Research (ZWO) are gratefully acknowledged.

Finally, I am deeply indebted to my wife Gisela for her effective spiritual and material support.

REFERENCES

Avé Lallemant, H. G., 1967. Structural and petrofabric analysis of an Alpine-type peridotite: the lherzolite of the French Pyrenees. Leidse Geol. Med., 42, pp. 1–57.

– & Carter, N. L., 1970. Syntectonic recrystallization of olivine and modes of flow in the upper mantle. Geol. Soc. Am. Bull., 81, pp. 2203–2220.

Blacic, J. D. & Christie, J. M., 1973. Dislocation substructure of experimentally deformed olivine. Contr. Min. Petr., 42, pp. 141–146.

Boland, J. N., 1976. An electron microscope study of dislocation image contrast in olivine $(Mg, Fe)_2SiO_4$. Phys. Stat. Sol., 34, pp. 361-367.

–, Mc Laren, A. C. & Hobbs, B. E., 1971. Dislocations associated with optical features in naturally deformed olivine. Contr. Min. Petr., 30, pp. 53–63.

– & Buiskool Toxopeus, J. M. A., 1977. Dislocation deformation mechanisms in peridotite xenoliths in kimberlites. Contr. Min. Petr., 60, pp. 17–30.

Buiskool Toxopeus, J. M. A., 1976. Petrofabrics, microtextures and dislocation substructures of olivine in a peridotite mylonite (Alpe Arami, Switzerland). Leidse Geol. Med., 51, pp. 1–36.

–, 1977. Fabric development of olivine in a peridotite mylonite. Tectonophysics, 39, pp. 55–72.

–, 1977a. Deformation and recrystallization of olivine during mono- and poly-phase deformation, a transmission electron microscope study. Neues Jahrb. Min. Abh., in press.

– & Boland, J. N., 1976. Several types of natural deformation in olivine, an electron microscope study. Tectonophysics, 32, pp. 209–233.

Calon, T. J., 1977. Structure and metamorphism of the alpine-type peridotite at Kittelfjäll, Swedish Caledonides. In press.

– & Buiskool Toxopeus, J. M. A., 1977. Development of olivine microstructures and dislocation substructures during polyphase deformation of an alpine-type peridotite. In press.

Carter, N. L. & Avé Lallemant, H. G., 1970. High temperature flow of dunite and peridotite. Geol. Soc. Am. Bull., 81, pp. 2181–2202.

Collée, A. L. G., 1962. A fabric study of lherzolites with special reference to ultrabasic nodular inclusions in the lavas of Auvergne (France). Leidse Geol. Med., 28, pp. 1–102.

Green, H. W., 1976. Plasticity of olivine in peridotites. In: Electron Microscopy in Mineralogy. Editor: H. R. Wenk. Springer Verlag, Berlin, pp. 443–464.

– & Radcliffe, S. V., 1972. Deformation processes in the upper mantle. Geophys. Mon., 16, pp. 139–156.

Kohlstedt, D. L., Goetze, C., Durham, W. B. & Vander Sande, J. B., 1976. New technique for decorating dislocations in olivine. Science, 191, pp. 1045–1046.

Möckel, J. R., 1969. Structural petrology of the garnet peridotite of Alpe Arami (Ticino, Switzerland). Leidse Geol. Med., 42, pp. 61–130.

Phakey, P., Dollinger, G. & Christie, J. M., 1972. Transmission electron microscopy of experimentally deformed olivine crystals. Geophys. Mon., 16, pp. 117–138.

Raleigh, C. B., 1968. Mechanisms of plastic deformation of olivine. Jour. Geophys. Res., 73, pp. 5391–5406.

Tex, E. den, 1969. Origin of ultramafic rocks, their tectonic setting and history. Tectonophysics, 7, pp. 457–488.

White, S., 1977. Recrystallization and textural development in naturally deformed quartz. Proceedings of the 4th European Texture Conference, in press.