Deformation Mechanisms, Rheology and Tectonics
THIS VOLUME IS DEDICATED TO THE WORK OF HENDRIK JAN ZWART
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Preface

It is my great pleasure to introduce this volume dedicated to my long-standing colleague and friend, Henk Zwart; the more so since I missed the opportunity of addressing him on the occasion of his retirement from the chair of structural and applied geology in the State University at Utrecht in 1988.

Hendrik Jan Zwart enrolled as a student of geology in the State University at Leiden in 1946. In my welcome speech as chairman of the student’s geology club at that time I included him among the ‘rolling stones of the post-war basal conglomerate’ of enrollment, and I must admit that he has never gathered any moss!

Although initially absorbed by Quaternary geology, Henk opted for structural geology at a later stage taking his MSc and PhD with L. U. de Sitter as supervisor. At that time the stamping ground of de Sitter was located in the soft-rock sector of the central Pyrenees, but Henk managed to persuade de Sitter (no mean task anyway!) to let him study the crystalline basement of the Saint Barthélemy Massif for his dissertation.

Armed with the structural and petrographic experience gained from this study of first honours degree quality, he began to apply microstructural techniques to the study of dynamothermal rock sequences in the central Pyrenees. With great insight, enthusiasm and perseverance he established himself as a pioneer in the meso- and microstructural fields, proposing clear criteria and a useful reference matrix (popularly known as Zwart’s Chicken Pen) from which the thermal and dynamic history of a metamorphic orogenic belt can be deduced.

After three years of tenure of the chair of geology in the University of Aarhus, where the Caledonides of Sweden came within his compass, Henk was invited to return to Leiden in 1969 to succeed de Sitter in the chair of structural and applied geology. With his collaborators and students he set out to compare the structural and metamorphic histories of the Pyrenees, the Caledonides and the Alps leading to his concept of the dualism of orogenic belts. Close collaboration with British and Australian workers in the microstructural field, some of whom were persuaded to join his staff, led to the establishment of a sort of Anglo-Dutch school. Moreover, much credit is to be given him for building up a first-rate structural laboratory, first at Leiden and later in Utrecht as well.

Enterprising as he is, Henk took the initiative to organize an international seminar on ‘Fabrics, microstructures and microtectonics’ that was held near Leiden in 1976, thus paving the way for biennial meetings on similar topics which have created a close fraternity and a fruitful integration of a broad gamut of structural disciplines. The Leeds Meeting on Deformation Mechanisms, Rheology and Tectonics is the latest in this series.

His international reputation gained even more from the almost Sisyphean task of editorship of the Metamorphic Map of the World, carried out at the request of the IUGS between 1966 and 1974. It was not surprising that he was then asked to occupy a number of important offices in the framework of IUGS: as secretary and later chairman of the Commission on Tectonics, as member of several working groups of the Interunion Commission on Geodynamics, and lately in the Interunion Commission on the Lithosphere of which he is at present the Secretary-General.

These merits of Henk Zwart formed the basis for his election as Member of the Royal Netherlands Academy of Sciences and Arts, and for the award of the prestigious van Waterschoot van der Gracht Medal by the Royal Netherlands Geological and Mining Society.

In conclusion I should like to mention that Henk’s personality is greatly appreciated by his colleagues, co-workers and students alike. I wish Henk every conceivable pleasure and satisfaction in his years of retirement.

Emile den Tex
Foreword

This volume is a collection of 47 original research and review papers on the theme of Deformation Mechanisms, Rheology and Tectonics. It is dedicated to Prof. Henk Zwart, on the occasion of his 65th birthday, in recognition of his own personal contributions to this subject area and of the stimulus he has provided to its development, particularly in Europe. An important part of this stimulus was the first international conference on tectonics and microstructures which he organized in Leiden in 1976, and which was the forerunner of a highly successful series held at various European centres since then. Most of the papers collected here were presented at the latest of such meetings, held at Leeds University in March 1989.

The papers are gathered into groups which are aimed at reflecting current research themes, ranging from geologically-oriented rock mechanics, through structural and microstructural studies of naturally-deformed rock masses to large-scale tectonics. In some cases thematic groups contain a ‘keynote’ paper, containing a substantial review component. The thematic grouping adopted for the present volume has, of course, depended on the nature of the papers submitted, so that not all of the sections contain review papers. Such papers will present an introductory framework for those new to the subject but the volume is dominated by original research papers.

To some extent the grouping of papers into thematic sets is arbitrary, because common threads often link the various sections. One of these is the role of water in rock deformation. The first section is headed ‘Role of fluids in rock deformation’, but various aspects of the role of water recur in later sections. Carter et al. provide a concise yet comprehensive review of the topic. The following paper by Sibson discusses the idea that a fault may periodically allow the drainage of a volume of high-pressure water which it intersects, following a seismic event: the ‘fault-valve’ hypothesis. Finally, Evans describes the role of water in the chemical alteration of granitic rocks, in turn modifying their deformability.

The following section deals with aspects of rock fracture and faulting. Contributions range from observational (Agar; Hippler & Knipe; Main et al.; Zulauf et al.; Stewart & Hancock), through mechanical experiments (Cox & Wong) to attempts at modelling aspects of brittle rock failure in compression (Casey & Wust; Cox & Paterson; Wong). Agar describes the temporal evolution of fracturing, hydrothermal alteration and mineralization of upper oceanic crustal rocks from a DSDP borehole. Hippler & Knipe describe the mierostructural modification of a pre-existing plastic mylonite during a superposed event causing cataclastic granulation. Main et al. review theoretical and experimental studies of the distribution of flaw sizes in rock bodies, from microcracks to lithospheric faults. These commonly exhibit scale invariance over a range of length scales, each characterized by a particular fractal dimension. The geometric configuration of flaws is expected to be important in the failure behaviour, and the authors develop a fracture mechanics model for the temporal variations of the fractal dimension. Zulauf et al. describe the microstructures of cataclastically deformed rocks from the KTB-VB pilot research borehole, which is close to the site of the projected German superdeep hole. Finally, Stewart & Hancock describe the characteristics of brecciation and damage in the near-surface region during the upwards penetration of extensional fault tips in the Aegean region.

Until recently, experimental studies of rock friction have been limited by attainable shear displacements of only a few millimetres. Rotary shear experiments are important way of overcoming this problem, but another approach is described by Cox in this volume. He uses a large direct-shear configuration in which large effective displacements are accumulated through repeated reversals of the direction of motion. He uses the state-variable friction-law approach to describe the results of velocity-stepping experiments, and finds that a friction law with two state variables is required to describe the experimental results.

Increasing amounts of effort are being applied to the problem of the theoretical description and modelling of the accumulation of damage (in the form of oriented arrays of extensional cracks) during loading of a brittle rock through failure. Related to this is the problem of instability, and whether the failure remains distributed (macroscopically ductile) or becomes localized into bands or faults. Three papers in this volume address the former question. Casey & Wust use a finite element approach to estimate the anisotropic elastic properties of rocks containing a regular array of oriented cracks. They show that a concentration of cracks in an inclined planar zone could result in an instability leading to shear faulting. Cox & Paterson take a similar approach to examine the
distribution of microcrack damage in a material modelled as a collection of deformable elements with a specified distribution of strength and elasticity. Finally, Wong describes experimental results on pore collapse in sandstones of a range of porosities, and uses these to help constrain fracture mechanics modelling of the process. He shows how the critical pressure for pore collapse depends on porosity and grain-size, and how volume reduction through pore collapse counteracts the destabilizing effects of dilatancy in the brittle deformation of low porosity rocks, favouring a degree of stable, cataclastic flow in porous rocks.

The mechanics of the development of instabilities during the deformation rocks, manifesting themselves as localized faults or shear zones, is receiving increasing amounts of attention, and it is appropriate that a section be devoted to a group of papers addressing this problem. A keynote contribution from Hobbs et al. attempts to apply a criterion of instability developed by materials scientists to rocks. Clarifying misconceptions which have crept into the geological literature, they show how zones of localized flow can develop even when the material within the zone does not suffer any change in rheological characteristics. Developing the same approach, Ord presents numerical models which display periodically-spaced localization of flow into shear bands, and discusses their significance for the focussing of fluid flow when the bands are dilatant.

There is a wide range of processes which modify rock properties and which can therefore favour localization of deformation. Some of these are illustrated by other contributions within the section. Olgaard shows how second-phase particles, through their inhibiting effect on grain-growth in rocks otherwise sufficiently fine to permit grain-size sensitive flow, can lead to petrographic controls on flow localization. Klaper describes an example of how softening associated with a metamorphic reaction appears to have led to flow localization. On a larger scale, using numerical modelling, Davies & Fletcher address the problem of localization of periodically spaced ramps in a duplex. Green & Burnley describe new high pressure/temperature experiments on Mg-germanate olivine which suggest that the instability which leads to deep-focus earthquakes might arise from the weakness of transiently ultralene-grained reaction products of the olivine-spinel transformation. Important new microstructural observations suggest that the instability may depend in some way on the coalescence into a fault plane of ellipsoidal ‘anticracks’, oriented normal to the compression direction. Although they draw analogy with the coalescence of axially-oriented cracks into a low-temperature brittle fault, further studies will be required to discover exactly how a discrete fault zone develops in this case. There is no doubt, however, that this will be a fruitful new line of research.

The formation of stylolites represents a particular kind of localization phenomenon in the flow of rocks by pressure solution. The paper by Carrio-Schaffhauser et al. describes a new and perhaps exotic way to examine them. They used X-ray tomography to construct a section through a stylolite, revealing the porosity structure ahead and on either side of the stylolite. Compared to the bulk rock remote from the stylolite the advance of the stylolite tip causes porosity increase, followed by porosity decrease as the stylolite tip passes through the 'process' zone.

Papers on intracrystalline-plastic and diffusional flow processes and the constitutive laws used to describe them are assembled in the following section. The rock deformation group at Utrecht have in recent years examined many aspects of the flow of halite rocks, and the first two papers (Franssen & Spiers; Spiers et al.) deal with this material. The former considers the implications of mechanical behaviour for the rate controlling process in intracrystalline plasticity. The latter attempts to draw together and synthesize the considerable body of data they have assembled on flow and compaction by pressure solution of halite. Recognizing that in nature halite shows evidence of flow both by pressure solution and intracrystalline plasticity, they attempt to assess the natural conditions under which the mechanism transition occurs.

The concept of 'superplasticity' applied to rock deformation has long been contentious. Whilst there is an argument for a purely geometric definition (the capacity for an 'extreme' degree of ductile strain, but without the deformation mechanism being specified), there is compelling reason in this case for associating the term with diffusion- or plasticity-accommodated grain-boundary sliding. In their paper, Gilotti & Hull express the former view. However, there was strong dissent amongst the referees of this paper, all three of whom raised the point that during rock deformation under entirely compressive stresses several mechanisms are capable of accommodating extreme strains. Readers are left to form their own opinions, or perhaps to doubt the advisability of using the term at all in the Earth sciences.

The following two papers are on themes related to the superplasticity issue. Burkhard describes the microstructural characteristics of highly deformed micritic limestones from the Alps and
interprets them in terms of flow by grain-boundary sliding. Walker et al. describe a sequence of high temperature experiments on synthetic, hot-pressed calcite rocks of controlled fine grain-sizes. These demonstrate grain-size sensitive flow of calcite rocks by grain-boundary sliding and the transition to relatively grain-size insensitive plastic flow with increasing grain-size.

Retaining the theme of calcite deformation, de Bresser & Spiers describe high-temperature experiments on calcite, in which they find that \( r^+ \) and \( f^+ \) slip in a single crystal is characterized by much more non-linear flow than in a polycrystal at the same temperature.

Understanding the apparent weakening role of water in the plastic flow of quartz has proved remarkably difficult, despite a quarter-century of effort. Paterson & Luan review the ‘state of the art’, to which Paterson and his coworkers have made seminal contributions. They argue that except for vacuum dried sample materials, the flow law parameters, stress exponent and activation enthalpy, are not significantly different in most of the experimental programs which have been run, and that water activity affects mainly the pre-exponential ‘constant’ in the flow law. They suggest a ‘representative’ quartz rheology and argue that apparent stress exponents of less than 4 in the flow law may be ‘unnatural’ owing to undesirable contributions (in experiments) from cracking and partial melting. In a second paper dealing with quartz deformation, Prior et al. use variations in recrystallized grain-size around rigid inclusions, together with stratigraphic constraints on strain-rates, to infer rates of microstructural equilibration in mylonites. The final two papers in the section are concerned with transmission electron microscopic studies of dislocation microstructures in hornblende (Skrotzki) and albite (White) in mylonitic rocks.

Five papers follow, dealing with aspects of measurement and interpretation of crystallographic fabrics in deformed rocks. Law provides a review of some of the recent work in this field, emphasising the ways in which petrofabric studies can be used to help solve problems in tectonics (an aim which this conference and proceedings was intended to stimulate). By means of numerical simulations, Jessel & Lister attempt to predict quartz fabrics that might arise from the combined operation of intracrystalline slip and ‘selective’ dynamic recrystallization, recognizing that the fabric types might change with temperature, owing to changes in relative critical resolved shear stresses for slip on different systems and the facilitation of recrystallization with increasing temperature. Ree effectively deals with the same problem, but by means of high homologous temperature deformation experiments using octachloropropane as a mineral analogue. In these experiments dynamic grain-growth makes a major contribution to the final microstructure. Olesen & Schmidt provide an example of the utility of electron channelling in the scanning microscope for petrofabric studies. They show that Dauphiné twinning in quartz can be detected by electron channelling but that Brazil twins cannot. Finally, Schaeben et al. provide an illustrated account of a method of calculating the orientation distribution function from pole figure data, subject to the maximization of an entropy-like function.

Going hand-in-hand with the exploration of submarine accretionary complexes by drilling and seismic profiling is a growing appreciation of the rock types and their mechanical properties in such complexes. The following section, entitled ‘Deformation of Weak Sediments’ commences with an assessment (Karig) of the behaviour of the zone of active accretion at prism toes, taking into account their geometric characteristics and the growing body of experimental data on the mechanics of weak, water-saturated rocks. Yassir describes some new experimental data of this type on the undrained behaviour of a group of mud-volcano derived silty clays. Finally, Sassen et al. provide an illustrated account of a method of calculating the orientation distribution function from pole figure data, subject to the maximization of an entropy-like function.

The structural and microstructural study of eroded ancient accretionary and related rock types also provides information essential to the evolution of a model for this environment of natural rock deformation. The final two papers of this section provide examples of this type of study. Nell infers deformation mechanisms from the structures and microstructures of melange belts on Alexander Island, Antarctica, and Pickering et al. examine the relationships between veins and pore fluids during the deformation of Miocene volcanioclastic rocks of SE Japan.

In the following section, on analogue modelling of the development of large-scale structures, Liu & Dixon describe centrifuge models which show how duplex structures throughout a wedge-shaped ‘thrust-belt’ can be continuously activated in order to maintain the equilibrium geometry of the wedge. McClay describes a suite of scaled models which demonstrate stages in the development of extensional fault systems and the way in which the underlying detachment configuration controls the cover fault template development. In a third paper using analogue modelling methods, Wilson & Will demonstrate the formation of slickenline features on a fault surface when the wall-rocks are themselves non-rigid.

The volume is concluded with a section which we have entitled ‘Deformation mechanisms and
tectonics'. In this we have grouped contributions which attempt to use structural and microstructural observations to help constrain interpretations of large-scale tectonic processes. Gratier & Gamond discuss the range of mid-crustal processes which can occur under conditions commonly equated with the 'brittle-plastic' transition, and which complicate the oversimplified interpretations commonly made of the depth limit of shallow seismicity. Coli & Sani and Sani describe occurrences from two different parts of the northern Apennines (Italy) of relationships between vein formation and overthrusting. Holdsworth & Grant attempt to relate 'anomalous' shear sense observations in the Moine nappe of N Scotland to dynamic spreading of the orogenic wedge. Iliffe & Lerche describe numerical modelling experiments which attempt to predict zones of sedimentary compaction associated with rotation of fault blocks. Finally, Urai et al. describe the microstructures produced during Alpine deformation and metamorphism on Naxos (Greece), and show how shear sense indicators most consistently indicate extensional unroofing of the higher-grade metamorphic complex through movement of the upper plate towards the north.

In conclusion, we would like to express our appreciation to all those who have been instrumental in bringing to fruition the conference and the present volume of proceedings. These are the members of the organizing committee, the referees of the 65 submitted papers (listed below), staff and graduate students of Leeds University Earth Science department, staff of the Geological Society Publishing House and the meeting sponsors (listed below) and exhibitors whose financial contributions helped defray costs.

E. H. Rutter & R. J. Knipe
March 1990
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