

ANALYSIS OF RUPTURED PEBBLES
IN THE MIERES CONGLOMERATES
N. W. SPAIN

by

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ABSTRACT

A multi-scale study of cataclastic deformation within a unit of tectonically-loaded, clast supported pebble conglomerates is presented. Stress-induced intragranular extension fractures radiate from points of contact between pebbles, and comparisons with photoelastic studies in granular aggregates suggest that fracture orientations and densities are controlled by heterogeneously distributed stress concentrations at pebble boundaries. Most fractures are of mode I extension type, although evidence for shear displacements is seen on some pebble surfaces. Indentation fracture theories are reviewed, and fracture mechanics equations are used to calculate the force required to cause failure of a pebble by the propagation of a throughgoing cone crack. Estimates are higher than tectonically reasonable values by a factor of 10, though the discrepancy is reduced through the incorporation of subcritical stress intensity factors in the analysis.

Fracture and crack orientations and densities are assessed in order to infer compression directions and relative levels of differential stress at the time of deformation. 3-dimensional fracture pole data is interpreted as resulting from a stress field which is heterogeneous along the 20km. strike of conglomerate exposure. A quantitative petrostructure technique, designed for use with a hand-digitizing pad and microcomputer, is developed to generate crack statistics from oriented hand specimens and reflected light photomosaics of thin sections. These are related to fracture pole data, but results are equivocal; meaningful 3-dimensional extrapolation of linear data requires extremely large sample sizes. Crack length histograms are presented, but these elucidate no meaningful correlations between crack length and observed density.

Pebble microstructures were studied using optical and SEM techniques. Three distinct modes of failure are inferred: (1) mode I transgranular cracks, (2) localized faulting through the coalescence of microcracks, and (3) more distributed cataclasis within localized zones. Transitions are interpreted in terms of variations in differential stress and effective confining pressure resulting from different packing configurations for a given pebble, as well as differences in initial microstructure - particularly the nature of cementation at grain boundaries.

CONTENTS

ABSTRACT		1
CONTENTS		2
ACKNOWLEDGEMENTS		7
CHAPTER 1.	INTRODUCTION	8
1.1.	GENERAL INTRODUCTION	8
1.2.	OUTLINE OF THE THESIS	10
1.3.	FRACTURE NOMENCLATURE	12
1.4.	FRACTURE MECHANICS	13
1.4.1.	Stress Intensity Analysis	15
1.4.2.	Critical Parameters for Failure	18
1.4.3.	Environmental Effects	19
1.5.	SCANNING ELECTRON MICROSCOPY	20
CHAPTER 2.	GENERAL ASPECTS OF PEBBLE DEFORMATION	24
2.1.	GEOLOGICAL SETTING	24
2.2.1.	DESCRIPTION OF CONGLOMERATE UNIT	26
2.2.2.	DESCRIPTION OF PEBBLE DEFORMATION	30
2.2.3.	MESOSCOPIC FRACTURE GEOMETRY	34
2.3.	DEFORMATION CHARACTERISTICS WITHIN PEBBLE AGGREGATES	38
2.4.1.	IMPINGEMENT FRACTURE THEORY	42
2.4.2.	STRESS FIELDS	43
2.4.2.1.	Hertzian Indenter	43
2.4.2.2.	Interpenetrating Contact	45
2.4.3.	MECHANICS OF FRACTURE	49
2.4.3.1.	Crack Initiation	49
2.4.3.2.	Propagation	50
2.4.4.	MODEL CALCULATIONS	54
2.5.	OBSERVED BEHAVIOR: A COMPARISON	58
CHAPTER 3.	CRACK AND FRACTURE ORIENTATION STATISTICS	64
3.1.	INTRODUCTION	64
3.2.	FIELD MEASUREMENTS	65
3.2.1.	Method of Analysis	65
3.2.2.	Results	66
3.2.3.	Discussion	69
3.3.	2-DIMENSIONAL DATA	78
3.3.1.	Sample Preparation	78
3.3.2.	Petrostructure Analysis	80
3.3.2.1.	Introduction	80
3.3.2.2.	Model Data	81
3.3.2.3.	Analysis	82
3.3.3.	Results	85
3.3.4.	Discussion	107
3.3.4.1.	Relationship Between 2-D and 3-D Data	107
3.3.4.2.	Relationship Between Cut Face and Thin Section Data	114
3.4.	CRACK LENGTH ANALYSIS	115
CHAPTER 4.	MICROSTRUCTURES OF DEFORMED PEBBLES	121
4.1.	INTRODUCTION	121
4.2.	MICROSTRUCTURAL DESCRIPTION	124

4.2.1.	Starting Material	124
4.2.2.	Modes of Failure	127
4.2.2.1.	Transgranular Cracking Along Discrete Surfaces	127
4.2.2.2.	Patchwork Cracking	128
4.2.2.3.	Faulting, Deformation Banding, and Distributed Cataclasis	129
4.3.	MORPHOLOGICAL CRACK CHARACTERISTICS	133
4.3.1.	Grain Boundary Assisted Transgranular Cracking	133
4.3.2.	Interactive Behavior in Patchwork Cracked Samples	137
4.3.3.	Microstructural Characteristics of Cataclasite Zones	142
4.3.3.1.	General Description	142
4.3.3.2.	Undeformed Appearance	145
4.3.3.3.	Structure Of Cataclasite Zones	146
4.3.3.4.	Behavior of Detrital Phyllosilicates	151
4.3.3.5.	Pore Filling Phases	152
4.4.	DISCUSSION	154
4.4.1.	Propagation of Single Cracks	154
4.4.2.	Crack Interactions	155
4.4.2.1.	En-Echelon Cracking	156
4.4.3.	Formation of Cataclasite Zones	159
4.4.4.	General Summary	162
CHAPTER 5.	CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK	166
5.1.	CONCLUSIONS	166
5.2.	SUGGESTIONS FOR FURTHER WORK	169
REFERENCES		172
APPENDIX A		180
A.1	INTRODUCTION	180
A.2	DIGITIZING ROUTINES	182
A.2.1	General Description	182
A.2.2	The Grid System	182
A.2.2.1	Program MACDIGI	183
A.2.3.2	Program DIGICRK	186
A.3.	Program MPLOTG	189
A.4.	Program WFCOR	190
A.5.	Program HISTPL4	199

LIST OF FIGURES

1.1A,B	Stress and displacement fields of growing cracks, after Lawn and Wilshaw	16
C	Schematic plot of crack velocity vs. stress intensity factor, after Atkinson	16
2.1	Structural sketch of Cantabrian zone, after Julivert	25
2.2A	Location of thrust traces in wedge of Paleozoic sediments within Cantabrian zone,	27

	after Julivert and Arboleya	
B	Sketch of sedimentation relationships within Cantabrian zone, after Julivert	27
2.3	Distribution of Mieres conglomerate, after Corrales et.al.	28
2.4	Stress distributions within granular photoelastic aggregate, after Gallagher et.al.	36
2.5	Pebble-to-pebble fracture maps of roadcut sections	41
2.6	Stress fields associated with Hertzian indenter, after Lawn and Wilshaw	44
2.7	Stress fields associated with sliding indenter, after Hamilton and Goodman	44
2.8	Stress fields associated with interpenetrating indenter, after McEwan	47
2.9A	Plots of contact area vs. stress concentration for a range of indenter configurations, after McEwan	48
B	Parameters of Hertzian cone configuration, after Lawn and Wilshaw	48
C	Parameters of Roesler cone configuration, after Roesler	48
2.10	Plot of mechanical energy release rate function for cone crack propagation, after Lawn and Wilshaw	53
2.11	Stress fields and predicted fracture configuratins for different idealized load configurations, after Gallagher.et.al.	53
2.12	Crack tracings from planar cuts through several pebbles	63
3.1	Stereographic projections of fracture poles from field localities	67
3.2	Schematic sketch of possible fracture distributions from loaded pebbles	72
3.3	Schematic sketch illustrating nature of topographic offsets on pebble surfaces	74
3.4	Fault distributions within large, triaxially stressed laboratory specimens, after Aydin and Reches	74
3.5	Range of compression directions inferred from fracture pole data	77
3.6	Comparison of different hand-digitizing criteria used in this study.	83
3.7	Comparison of hand tracing and computer generated crack map from sample AB13	86
3.8	Sample localities for 2-D data	87
3.9-3.17	Crack orientation data and crack maps from hand specimens	88
3.18-3.22	Crack orientation data from thin sections	99
3.23	Mosaic crack map from Plate 3.7	106
3.24-3.26	Stereographic histograms relating crack data to field orientation	109
3.27	Integrated 2-D and 3-D orientation data	113
3.28,3.29	Crack length histograms for hand specimen crack maps	117
3.30	Crack length histograms from thin section	119

crack maps

4.1	Schematic illustration of modes of failure transitions in crustal rocks, after Rutter	123
4.2	Schematic sketch of crack-crack and crack-pore interactions, after Kranz	157
4.3	Stress distributions and predicted secondary fracture configurations for discontinuous, overlapping faults, after Segall and Pollard	157
4.4	Schematic sketch illustrating the effects of increasing confining pressure on microfault morphology, after Hadizadeh	164
A.1	Illustration of grid system and coding sequence used in digitizing mosaic crack maps	185
A.2	Summary flow chart of PROCANGLE	187
A.3	File entry sequence for 4 x 3 grid	187
A.4	Summary flow chart for Program WFCOR	193
A.5	Summary flow chart for PROCVERTES and PROCYCHECK	195
A.6	Summary flow chart for PROCHORTES and PROCXCHECK	196
A.7	Summary flow chart for Program HISTPL4	203

LIST OF PLATES

1.1	X-Ray spectra lines used to identify mineral phases in BSE micrograph of pore-fill.	23
2.1	General outcrop appearance of pebble conglomerate	29
2.2	Photographs of roadcut sections from which fracture maps in Fig. 2.5 were prepared	40
2.3	Detailed views of actual fracture configurations observed in deformed pebbles	59
2.4	Shear fractures in deformed pebbles	62
3.1	Photographs of pebble hand specimens	73
3.2-3.6	Reflected light photomosaics and corresponding computer generated crack maps from thin sections	100
3.2	ABI	100
3.3	ABIII	101
3.4	AB18	102
3.5	OL1	103
3.6	OL2	104
3.7	Photomosaic of part of specimen ABI used to prepare mosaic crack map of Fig. 3.23	104
4.1	Optical photomicrographs of undeformed (A,B) and transgranularly cracked (C-E) samples	125
4.2	Transmitted light photomicrographs from "patchwork" cracked samples	130
4.3	Reflected light photomicrographs of discrete crack surfaces	135

4.4	SEM (SEI mode) photomicrographs from discrete crack surfaces	136
4.5	Regular (A,B) and irregular (C,D) crack interactions in patchwork cracked samples	139
4.6	Macrocrack morphology (A,B) and pore interactions (C,D) in patchwork cracked samples	141
4.7	Optical photomicrographs from cataclasite zones	144
4.8	SEM photomicrographs of microstructures observed away from (A-C) and within (D) cataclasite zones	147
4.9	High magnification SEM micrographs of cataclasite zones	149
4.10	Nature of cataclasite zone walls (A,B) and behavior of detrital phyllosilicates (C,D) in samples which show well developed cataclasite zones	150
4.11	BSE photomicrographs comparing detrital and pore-filling phyllosilicate textures.	153

LIST OF TABLES

1.1	Fracture/crack nomenclature as used in this study	14
2.1	Summary of sedimentological features of Mieres conglomerate	31
4.1	Summary of microstructural features of specimens described in microstructural study	163
A.1	Variable descriptions: Program MACDIGI	188
A.2	Variable descriptions: Program WFRCOR	197
A.3	Variable descriptions: Program HISTPL4	206

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1.1 GENERAL INTRODUCTION

Despite its fundamental significance in determining the way in which geological materials deform, the role of stress in the faulting process remains rather inadequately understood. A characterization of the state of stress in an infinitely small volume of material is a fairly simple proposition; forces acting at the boundary of an element are resolved as tensor quantities on a given plane, and a set of transformation rules enables the determination of principal stresses for an arbitrary coordinate system. Unfortunately, the state of stress within a continuum is extremely inhomogeneous in time, and varies from point to point within a given body. A range of equilibrium equations must be solved to ensure that a body subjected to loading forces at its boundaries remains in equilibrium from point to point within the continuum. Stressed bodies usually respond to those loads by deforming, and complex strain fields arise as each point within the continuum displaces to a new position. The nature of those displacements is in turn determined by the particular rheological properties of the material. While it is often roughly possible to determine a set of vectors which relate the initial position of any point in a body to its position after deformation, it is generally impossible to determine either the exact path those particles followed during their deformation histories or the orientation and magnitudes of the principal stresses at a given instant in time. When one considers that the processes which effect geological deformation operate at physically inaccessible depths within the crust and at rates which are generally too slow to be monitored through direct observation, it hardly seems surprising that fundamental problems concerning the role of stress in controlling deformation remain to be solved.

In very broad terms, the research presented in this thesis has been motivated by a desire to investigate the manner in which stress influences both the mechanics and geometries of faults within the upper crust, which form via dominantly brittle processes at relatively low temperatures

and pressures. Previous attempts along similar lines can be crudely classed into three distinct categories, depending upon the particular approach followed:

1. ANALYTICAL MODELS. In general, these involve the derivation of exact mathematical expressions which relate the actual stresses and strains which arise due to loading by applied forces. Simplifying assumptions relating to distribution of forces or displacements at the material boundary (boundary conditions), material response, and rock homogeneity are often required to make the resulting equations tractable.

2. NUMERICAL SIMULATION STUDIES. These have come into increasing favor and more widespread use with the advent of large, high-speed digital computers. Some of the simplifying assumptions required in analytical models must be maintained (especially the approximation of the body as a relatively homogeneous continuum), but the investigation of much more complicated boundary conditions is possible. Stress and displacement functions are represented approximately at a large but finite number of points within the body, and solved using matrices of linear algebraic equations. The investigation of non-linear stress-strain behavior is possible by specifying different forms of material response at different stages in the load history. One such numerical technique, the finite element method, has been extensively employed in the analysis of a range of structural problems of interest to engineers, and more recently to geologists and tectonophysicists.

3. PALEOSTRESS DIRECTION INDICATORS.

Collaboration between structural geologists and rock deformation workers has led to the realization that certain structural features (e.g. joints, fractures, cracks, twin planes, and

faults) develop with a predictable geometric relationship to the principal stress tensor in rock masses. In regions where deformation has produced only relatively small amounts of permanent strain, it is often possible to infer the orientation and variation of principal stresses within the rock at the time of deformation. Studies have been made at a range of scales, from global dimensions using earthquake focal solutions, to millimeter-sized rock samples using grain-scale microcrack orientations. These approaches enable the spatial homo- or heterogeneity of principal stress orientations to be assessed, and often allow semi-quantitative inferences to be made regarding variations in stress magnitudes over a given area.

1.2 OUTLINE OF THE THESIS

The work reported in the chapters to follow fits squarely in the paleostress indicator category. Brittle deformation within a unit of clast-supported silicic conglomerates from a thrust sheet within the Cantabrian zone, which constitutes the foreland of the Hercynian orogenic belt in NW Spain, has been studied at a range of scales of observation. On the scale of individual outcrops dense sets of fractures, generally with widths of less than a millimeter, were observed to radiate from impingement contacts between pebbles. Previous reconnaissance examinations by workers at the University of Oviedo (Asturias, NW Spain) and Imperial College indicated that the fractures might be tectonically induced, since they seemed to develop with a distinct sub-horizontal orientation which would belie their interpretation as features relating solely to overburden stresses. The research project was designed to test those preliminary conclusions, and to further examine aspects of their deformation through a detailed microstructural analysis.

An attempt was made to characterize the deformation of the pebble aggregate in terms of packing geometries and load configurations; the results are reported in chapter 2. These are compared with previous rock mechanics and geological studies of the behavior of granular aggregates. Stress distributions arising at points of contact between indenting spheres are reviewed, and the brittle response of rocks loaded at points of impingement is considered in light of theories of indentation fracture within the materials science literature.

In chapter 3, the results of two different approaches to orientation analysis are presented and discussed. Three-dimensional measurements of fracture orientations were made at 4 separate field localities using a compass/clinometer. The findings are used to make preliminary paleostress inferences in the area of conglomerate exposure. Oriented pebbles were collected, and crack data from hand specimens and thin sections were generated. A series of microcomputer programs were developed for use with a hand-digitizing pad, in order to facilitate the handling of large sets of data from 2-dimensional sections. Using a method devised by Blenkinsop (1982), the two-dimensional results were related to the orientations of pebbles as recorded at the time of collection, and an attempt is made to determine 3-dimensional crack orientations from the 2-dimensional data. These are compared with the direct 3-D measurements to test the applicability of the technique. Crack length statistics are presented in an attempt to make quantitative inferences regarding stress magnitudes within individual pebbles.

In chapter 4, microstructural observations obtained using reflected, transmitted, and scanning electron microscopy (SEM) techniques are presented and discussed. An attempt is made to characterize modes of failure within individual pebbles, and the effect of initial microstructural variables (e.g. grain size, sorting, and mineralogy) and physical properties (e.g. confining pressure, total differential stress, strain rate, and pore fluid pressures) in determining mechanical behavior are considered in light of previous rock deformation experiments

and detailed microstructural studies. It is hoped that these results will help to determine the extent to which laboratory data can be extrapolated to problems of natural deformation.

Chapter 5 lists the general thesis conclusions and suggests further avenues of study which might follow directly from this work. Appendix 1 presents a detailed description of the microcomputer programs discussed in chapter 3, along with summary flow-charts and program listings. It is hoped that their incorporation and documentation will make them available for wider use.

1.3 FRACTURE NOMENCLATURE

Deformation within the conglomerate unit is almost completely cataclastic in nature. Stearns (1968) noted the essential characteristic of strain accommodation by cataclastic mechanisms:

"... Once a rock layer loses cohesion along fractures and separates into discrete parts, no matter what their size, it can begin to flow by 'displacements of constitutive parts' relative to one another by mechanical granulation, breaking, or crushing...."

Within the context of this study, size and fracture are both fundamental concepts. For field purposes, fracture can be said to occur on a pebble-to-pebble (mesoscopic) scale, and is easily observed with the naked eye. Displacement along these fractures can be normal or parallel to the surface (and in many cases is a combination of both), but the pebbles contain no lithological markers, and it is thus difficult to apply "direction of movement" criteria to individual fractures in the field. The problem persists at the thin section (microscopic) scale, although it is relatively easy to distinguish between microfaults, which contain crushed material along their surface, and cracks, which do not. Fractures which appear morphologically identical when viewed in hand specimen often appear to have formed by fundamentally different processes when viewed at the microstructural level. Because features observed are the

same (just viewed at different scales using different visual aids), the overlap in terminology results in a fair degree of confusion.

To help alleviate some of that confusion, I have described brittle phenomena with particular attention to scale of observation and extent of area affected. With reference to field observations, fracture is the commonly applied term. When describing microstructural characteristics, I prefer to subdivide structures as either transgranular cracks or microfaults (on the scale of many grains) and microcracks (on the scale of a few grains). I do not contend that the distinctions summarized in Table 1.1 are generally applicable to all cataclastically deformed rocks; I simply feel that they adequately describe the characteristics of the aggregate materials that comprise the subject of this study.

1.4 FRACTURE MECHANICS

The subject of "fracture mechanics" has evolved within the engineering fields as an approach to predicting the likelihood of fracture from pre-existing material flaws. In recent years, workers in the field of theoretical rock mechanics have increasingly applied the fracture mechanics approach to problems associated with the failure of rocks loaded in compression under conditions where dominantly brittle response is achieved. According to Paterson (1978) these studies are motivated by two general concerns:

1. The need for an adequate understanding of the local stress distributions in the neighborhood of a crack tip, and the relation of this stress field to the external loading of the body.
2. The desire to characterize the response of a given material to the state of stress at the crack tip.

Because continued reference is made to relevant fracture mechanics studies within the text of this thesis, and

because a range of fracture mechanics terminology is employed, a brief summary of the main features of engineering fracture mechanics is presented. Most of the points presented are taken directly from Paterson (1978), and interested readers are referred to the text by Lawn and Wilshaw (1975) for a more detailed presentation of the material. Three main topics are presented: (1) stress intensity analysis, (2) critical parameters for failure, and (3) environmental effects. These will serve as the basis for later discussion.

1.4.1 Stress Intensity Analysis.

Despite the fact that non-elastic effects occur in the immediate vicinity of the crack tip in most materials, the general analysis of stress distributions in the neighborhood of crack terminations proceeds via the classical theories of linear elasticity (linear elastic fracture mechanics). Provided that the region of crack-tip non-linearity is small when compared to crack length, the linear elastic approach provides a reasonably accurate analysis of the stress distribution around the crack in question. Stress intensity analysis focuses on the propagation stage of crack development, once a crack is said to be "well-developed"; by providing a measure of the loading applied to the crack tip from external forces, it enables one to estimate its tendency to spread.

Stress Distributions Within the Crack Tip Region.

The simplest analysis of crack-tip stresses involves the use of the "sharp-slit" approximation; the crack is assumed to be perfectly planar, with a sharp tip in the unstressed state. Three basic plane modes of distortion around the tip are considered, defined with respect to a reference plane that is normal to the straight-line crack front, as summarized in Figure 1.1A:

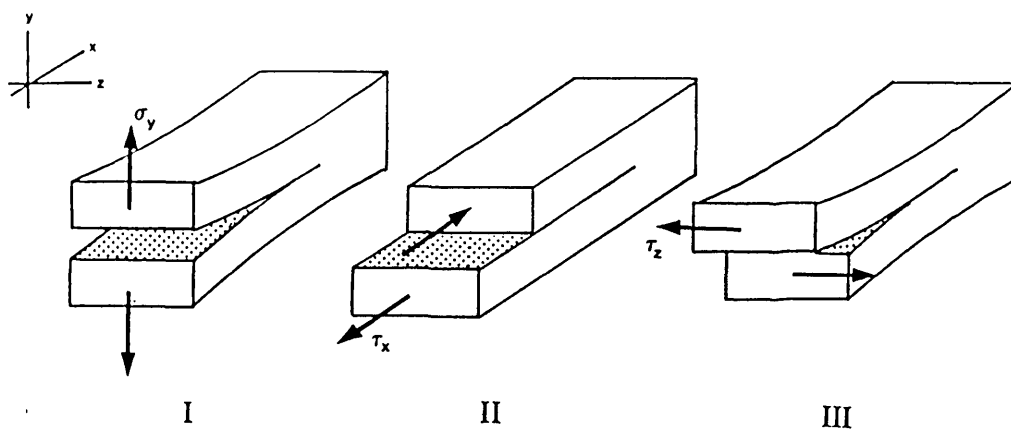
1. Mode I-opening mode- corresponds to normal separation of the crack walls.

FIGURE 1.1A. The three modes of fracture, as described in text: I, opening mode; II, sliding mode; III, tearing mode. After Lawn and Wilshaw (1975).

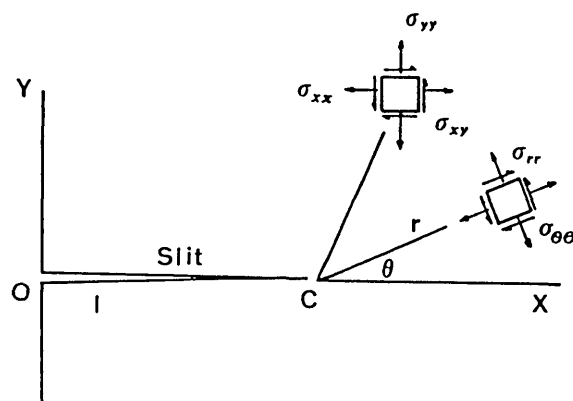
FIGURE 1.1B. Stresses around the tip of a "sharp-slit" crack, showing rectangular and polar coordinate components in reference frame of 1.1A. After Lawn and Wilshaw (1975).

FIGURE 1.1C. Schematic stress intensity factor (K_I)-crack velocity (v) curves. The threshold stress intensity factor (K_{I0}) and the critical stress intensity factor (K_{Ic}) are shown. After Atkinson (1982).

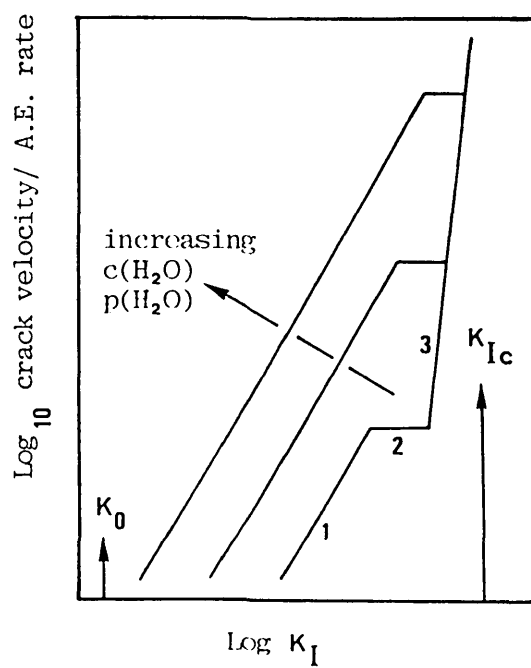
A



B



C



ii. Mode II- sliding mode- corresponds to mutual shearing of the crack walls perpendicular to the crack front. Points on the crack surface are displaced in the reference plane.

iii. Mode III- tearing mode- corresponds to mutual shearing of the crack walls parallel to the crack front. Points on the crack surface are displaced normal to the reference plane.

Stress and displacement fields around the crack tip are obtained by considering distortions as resulting from the application of uniform loads at infinity, in the absence of crack perturbations. These correspond to uniform tensile stress normal to the crack plane (mode I), a uniform shear stress parallel to the crack in the x-direction (mode II), and a uniform shear stress parallel to the crack in the z-direction. These are also shown in figure 1.1A.

Using the sharp-slit approximation, Lawn and Wilshaw (1975) present the general expression for crack tip stress and displacement fields, as a product of a spatial distribution function that is independent of the actual value of applied stress, and a scaling function that depends on the applied stress and crack length. Figure 1.1B outlines the rectangular and polar coordinates for a general sharp-slit configuration. Solutions for stress are of the form:

$$\sigma_{ij} = K(2\pi r)^{-1/2} f_{ij}(\theta) \quad (1)$$

and displacements are given by:

$$u_i = (K/2E)(r/2\pi)^{1/2} f_i(\theta) \quad (2)$$

where values of K are the stress intensity factors for a given mode (i.e. the scaling factor), E is Young's modulus, and $f(\theta)$ is an angular function determining stress field distribution.

Two important points are noted. First, stress

components vary inversely as the square root of the distance from the crack tip in all radial directions, although angular singularities introduced by the sharp-slit approximation render the expression invalid for very small or very large values of r . Second, stress intensity factors are additive for a given mode of opening, since the principle of superposition applies to linear displacements and stresses. Most general cases of distortion can thus be treated as a combination of the three basic modes. The actual values of K will depend upon the macroscopic stress field and the geometry of the specimen. For the specific case of the pebbles of the Mieres conglomerate, these geometries are governed by the exact configuration of pebble-to-pebble impingements. Derivation of these stress solutions are discussed in detail in the next chapter.

1.4.2 Critical Parameters for Failure

The general stress intensity analysis outlined above enables one to describe the general situation around a crack tip. It is then necessary to characterize the tendency for the crack to spread under the action of increased external load. An energy approach common to many theoretical studies of brittle failure involves the application of thermodynamic considerations, which equate the change in applied load to the energy created by crack extension, which can be subdivided into the elastic strain energy released and the surface energy created. This aspect of crack propagation is discussed in the next chapter; here it is only important to note the existence of a parameter known as the mechanical energy release rate function, G . The standard fracture mechanics approach employs this parameter in developing criteria for local failure. The criterion for catastrophic crack propagation is expressed in terms of critical stress intensity factors, which are material parameters that depend upon the exact physical properties of the specimen, and are designated as K_{Ic} , K_{IIc} , and K_{IIIc} according to the mode of opening. For mode I extension, G can be related to K_{Ic} by the expression:

$$G = (1-\nu^2)/E \times K_{Ic}^2 \quad (3)$$

or for the more general case of a combination of modes, the critical parameters for failure are related by:

$$G_c = (1-\nu^2)/E \times (K_{Ic}^2 + K_{IIc}^2) + K_{IIIc}^2/2G \quad (4)$$

where E, G, and ν are Young's modulus, the shear modulus, and poisson's ratio respectively.

For practical purposes, the critical stress intensity expressions are very powerful, since they enable the actual crack geometry and precise material behavior to be incorporated in one material constant, which can be evaluated empirically. They do not, however, adequately describe crack behavior under conditions of long term loading. Various environmental factors generally can combine to allow a significant amount of crack extension at values of stress intensity factor substantially below K_{Ic} . This phenomena, known as subcritical or stable crack growth, is discussed below.

1.4.3 Environmental Effects

A range of competing mechanisms, some dependent upon the chemical environment of the deforming system, affect the kinetics of crack propagation and allow stable crack growth to proceed. The subject has received a considerable amount of attention in the geologic literature, and the reader is referred to comprehensive reviews by Anderson and Grew (1977) and Atkinson (1984) for a detailed treatment. While a range of mechanisms have been called upon to explain subcritical crack growth (e.g. dissolution, crack-tip diffusion, ion-exchange, microplasticity), stress corrosion is probably the best understood and most extensively documented process. In general terms, it involves the weakening of strained bonds at crack tips by a chemical agent such as water. Crack growth occurs at velocities which decrease from K_c to some threshold level below which no crack propagation is commonly observed.

Figure 1.1C shows the relationship between crack velocity and stress intensity factor for subcritical tensile crack growth, and the idealized diagram displays the typical trimodal behavior commonly seen in experiments on glass. The shape of the corresponding curve for most common rock types has yet to be determined, though experiments on quartz suggest that the three-stage behavior clearly applies.

A growing body of experimental fracture mechanics data is now available for a range of geologic materials, though several questions must be answered before the laboratory data can be extrapolated to natural deformation conditions with any degree of certainty. A range of variables are known to significantly affect the kinetics of crack growth, and uncertainties concerning the range of values possible for each complicate the overall picture. These controlling factors include temperature, grain size, microstructure, and residual strain. An attempt is made to quantify certain aspects of crack propagation within the pebbles of the Mieres conglomerate, but it must nonetheless be noted that while trends for given parameters are reasonably well-understood, the exact values for a host of parameters are still the subject of a great deal of uncertainty.

1.5 SCANNING ELECTRON MICROSCOPY

During the microstructural study (chapter 4), it was determined that the high resolution optics available with the SEM were required to resolve the physical characteristics of grain boundaries and micron-width microcracks. Specimens were examined using a JEOL JXA SEM/microprobe equipped with an X-ray energy dispersive (EDS) spectrometer. The instrument affords several distinct "modes" of analysis, and two of these were used extensively and simultaneously throughout this study. To assist the reader uninitiated in the fundamentals of SEM analysis, the differences between the modes are briefly reviewed, in order to avoid confusion with some of the terminology used to describe micrographs in chapter 4. The account follows

from Lloyd (1985) and White et.al. (1984).

Secondary Electron Emission (SEI mode)

In all SEM modes of operation, a target specimen is irradiated by a finely focused beam of electrons. In SEI mode, loosely bound target electrons are excited by inelastic collisions with the beam. As the electron beam scans over the target, it stops on a finite group of points for a short period of time, and receives a set of signals. Images appear because signal intensity generally varies between scanned points. Contrast is observed in SEI images because the yield and intensity of escaping electrons is sensitive to the angle between the beam direction and the normal to the surface of the target. Target surfaces inclined at high angles to the incident beam emit more electrons than those with a lower tilt, and thus the SEI image is one of surface topography. Within the samples studied here, crack traces and boundaries between clay minerals and quartz were readily distinguishable, since the abrasive materials used during polishing preferentially attacked both crack filling phases and clay minerals.

Backscattered Electron Emission (BSE mode)

Backscattered electrons are incident electrons which have been reflected back by predominantly elastic scattering events. The fraction of electrons backscattered increases with increasing atomic number (Z), and by placing a suitable detector in the electron path it is possible to study compositional differences between and within individual mineral phases. Minerals with higher atomic number appear brighter on the screen.

Using the EDS X-ray spectrometer controlled by a Link Spectra System, it was possible to perform both qualitative and quantitative mineral analyses on individual grains, and thus determine the composition of crack and pore-filling phases within the pebble microstructures. Since quantitative mineral analyses were considered to be beyond the requirements of this study a qualitative determination

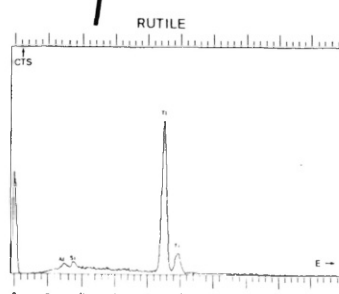
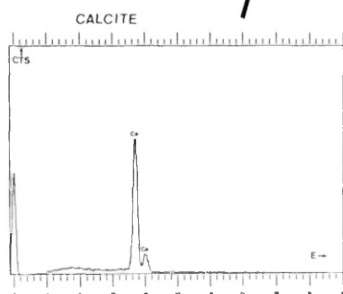
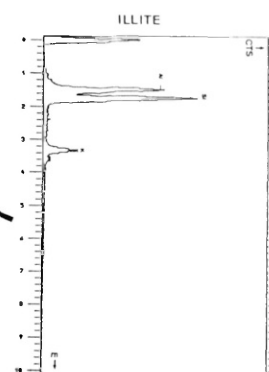
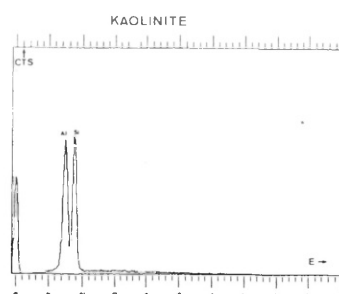
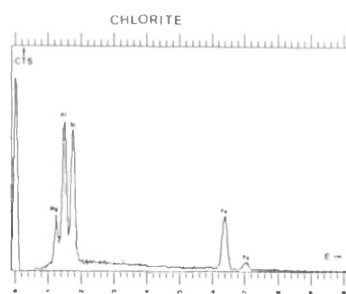
of phases showing different BSE contrast was made. Elements within a selected "spot" are identified, an X-ray spectrum is produced, and major X-ray lines are identified by comparing their energies with a list of possible X-ray lines known to occur at that energy. When element analyses are combined with the BSE contrasts seen on-screen, phases can usually be readily identified.

Plate 1.1 shows the general approach as applied to a portion of a thin section from one of the pebbles. The photograph is in BSE mode, and contrast between phases is apparent. X-ray spectra from point analyses at 5 locations are shown, and lines point to the individual minerals, which are identified as illite, rutile, calcite, and fine interlayered intergrowths of kaolinite and chlorite. All mineral identifications from BSE micrographs were arrived at in this way.

PLATE 1.1.

X-ray spectra lines used to identify mineral phases within the backscattered electron (BSE) micrograph shown. The presence of individual phases is identified on the basis of atomic number contrasts, which produce signals of varying intensity for different minerals. Arrows point to the location of spot analyses, which are used to identify kaolinite, chlorite, calcite, rutile, and illite within the pore infill, as indicated on the spectra plots. Numbers in the bottom of the photograph refer, from right to left, to beam accelerating voltage, magnification/10, photo number, and scale (scale bar = 10um.)

PLATE 1.1



Chapter 2

GENERAL ASPECTS OF PEBBLE DEFORMATION

2.1 GEOLOGICAL SETTING

The Mieres conglomerate is part of a package of Westphalian (Carboniferous) synorogenic deposits which lie within the Cantabrian Fold and Thrust belt in NW Spain. The Cantabrian zone forms the frontal unmetamorphosed core of the Hercynian Orogenic belt (fig. 2.1), and is comprised of a package of arcuate nappes whose geometry is similar to that seen in other well known fold and thrust belts (Julivert and Arboleya, 1984). Julivert (1973) has proposed a model for the sedimentation-deformation relationships within the zone, and he outlines several stages of sedimentological development. These are briefly summarized, as they place the synorogenic deposits in an evolving deformational framework:

1. A thick clastic wedge of pre-Namurian Paleozoic sediments, thinning towards the east, was deposited in a platform environment on top of pre-Cambrian basement.
2. Orogenic activity within the internal zones of the developing Hercynian belt created gravitational slope instability, leading to local deposition of Namurian turbidites and isolated olistostromic deposits.
3. As a result of increased tectonic movements on eastward directed thrusts, emergent land provided a source for Carboniferous sedimentation. A 5000m thick sequence of paralic sediments was deposited in what is today known as the Central Coal Basin, within the center of an arcuate shaped mountain system. The Mieres conglomerate is exposed in the northwest corner of this basin, and presumably

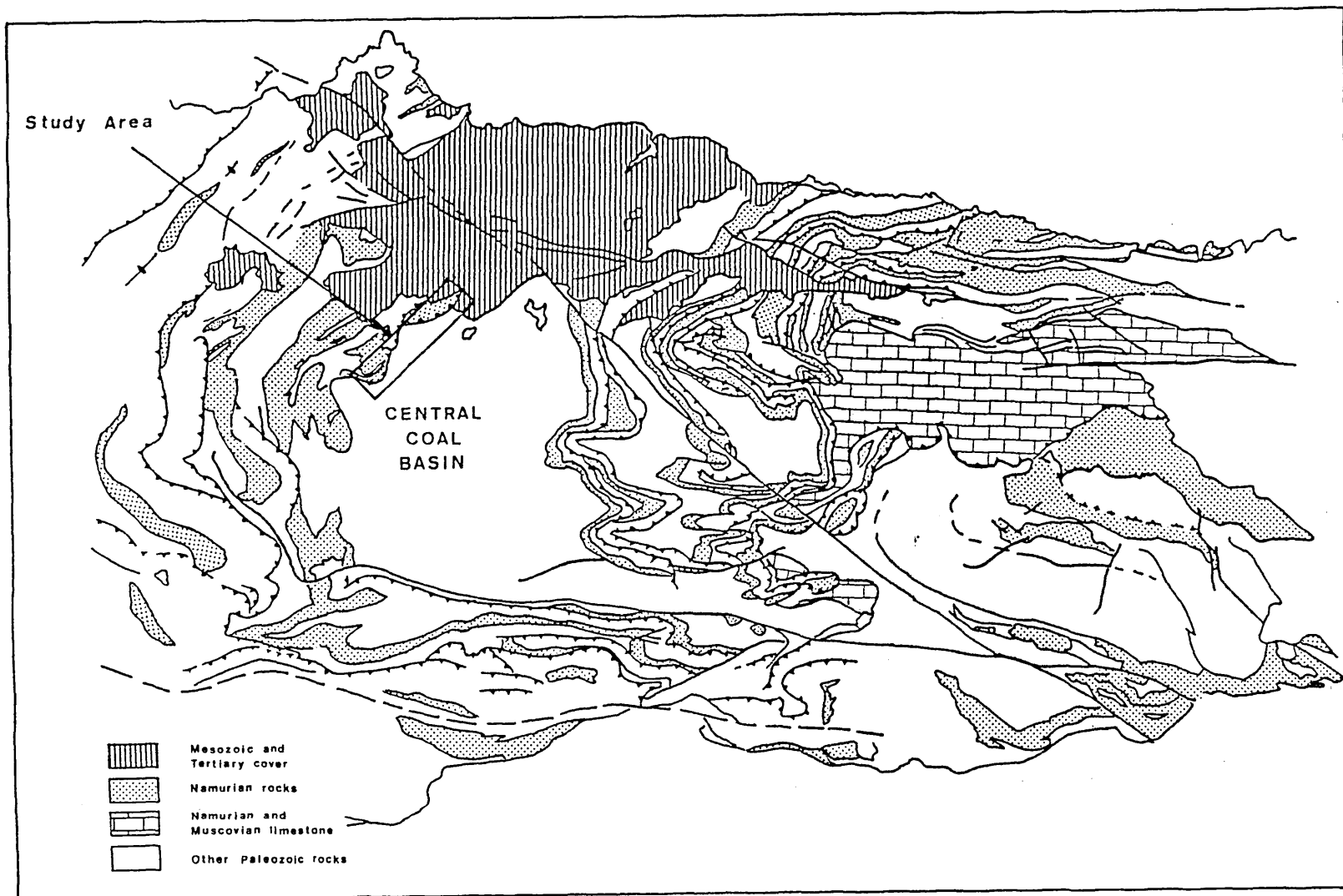


FIGURE 2.1. Structural sketch of the Cantabrian zone. Box indicates location of the study area. (After Julivert, 1978).

formed as a set of large fans being shed from a westerly source (fig. 2.2B). The Central Coal Basin formed as a large subsiding basin, and trapped the flow of terrigenous material which continued unimpeded both to the north and south to form thick sequences of Westphalian turbidites.

Figure 2.2A shows the geographical relationship between major thrust units and the position of the Mieres conglomerate. A northern splay off the La Sobia thrust separates the Coal Basin sediment units from a major stack of pre-orogenic Paleozoic sediments, and the fault contact lies less than one kilometer (in a direction perpendicular to the bedding-parallel thrust plane) from the top of the Mieres unit. The tectonic significance of this overlying thrust sheet will be discussed in Chapter 3, when the nature of the load which deformed the succession is considered.

2.2.1 DESCRIPTION OF CONGLOMERATE UNIT

The Mieres conglomerate forms a sedimentary succession with an average thickness of 670m, in beds striking NE-SW and dipping at angles of between 45 and 60 degrees NW. Lateral exposure is limited; the unit terminates within a distance of 20km along strike. In most outcrops the conglomerate is intensely weathered, and clean exposures with intact matrix occur in only 5 fresh roadcut sections. Figure 2.3 shows a sketch map of the unit; the location of the main localities is marked. Sedimentary features are relatively uniform from one locality to the next, but vary with vertical position in a given section. Plate 2.1a shows the general appearance of a typical roadcut as seen at a building site near Olloniego (see fig 2.3). Here bedding dips in the direction of the arrows; there is a clear suggestion of preferred clast alignment, with the long axes of individual pebbles aligned subparallel to bedding. Both the degree of sorting and mean pebble size are variable over the range of a given roadcut, and in some cases the

A

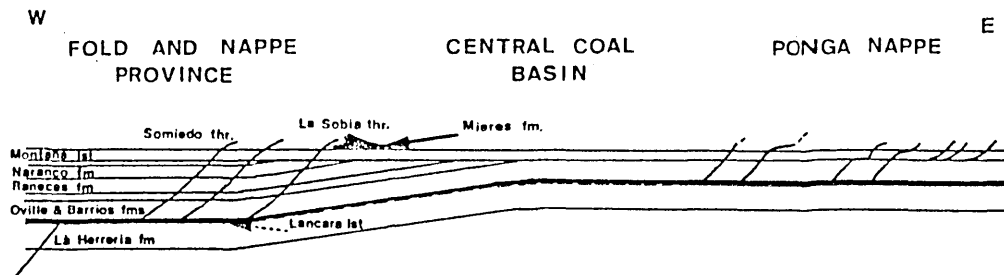


FIGURE 2.2A. Schematic cross section across the Northern Cantabrian zone, illustrating the position of thrust surfaces in the wedge of pre-Carboniferous sediments. (After Julivert and Arboleya, 1984).

B

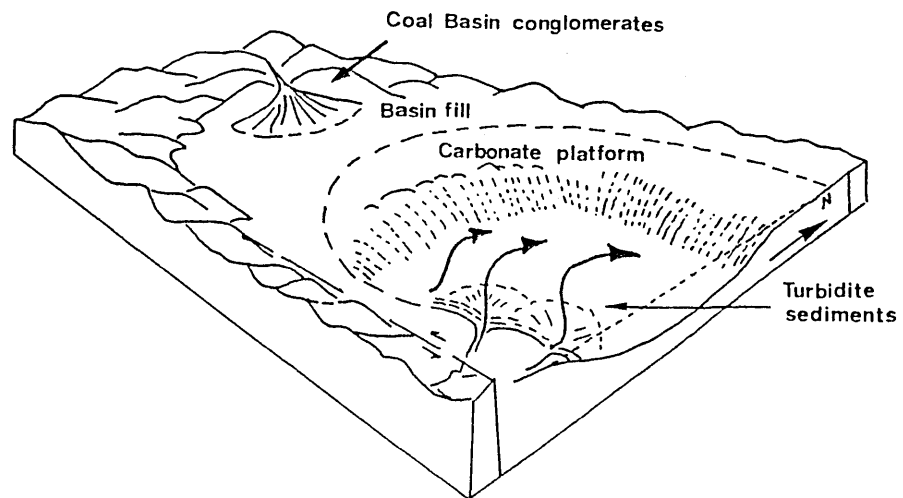


FIGURE 2.2B. Schematic interpretation of sedimentation relationships in the Cantabrian zone during Westphalian times. (After Julivert, 1978).

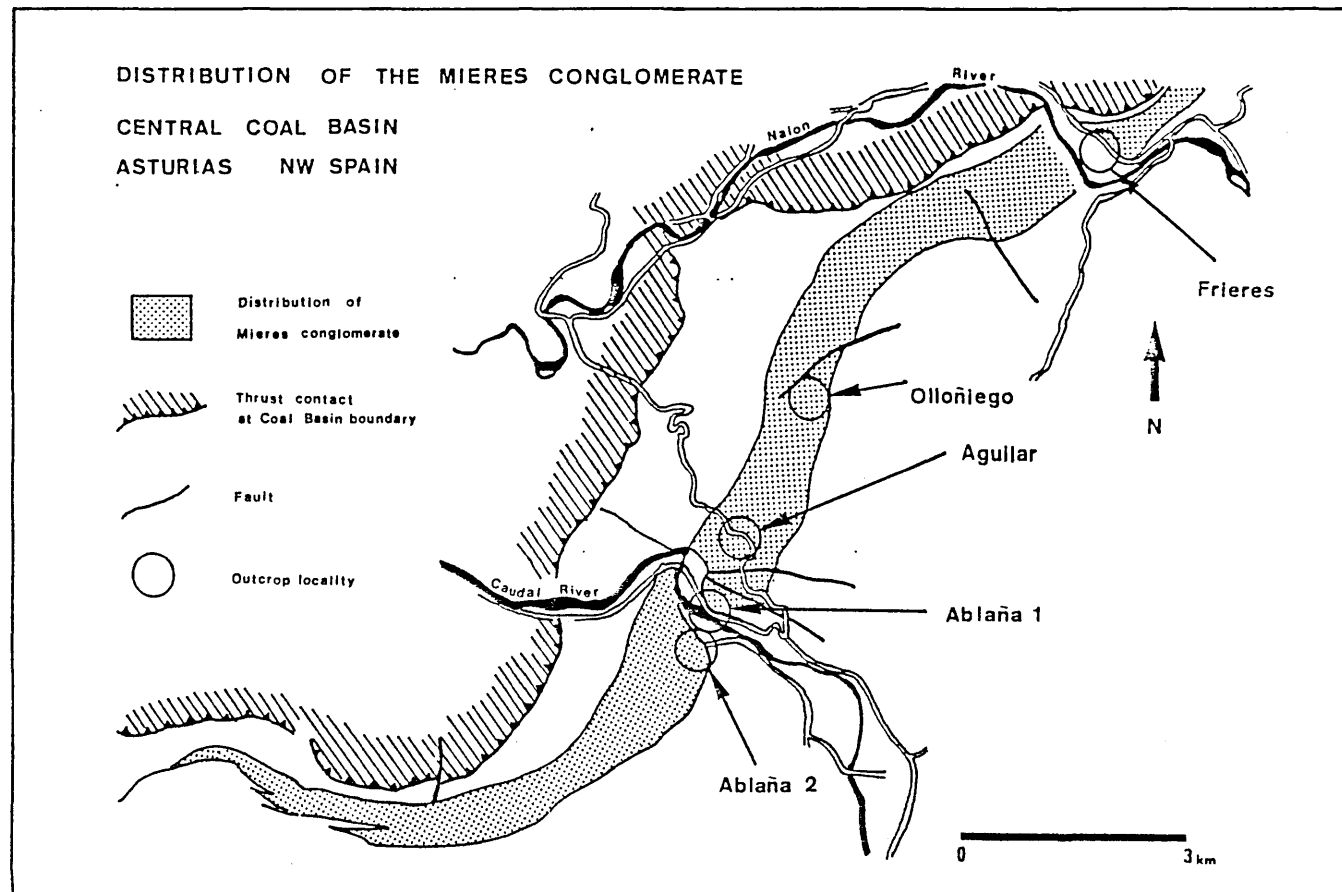


FIGURE 2.3. Map illustrating the present-day distribution of the Mieres quartzite conglomerate. Outcrop localities visited during this study are circled. (After Corrales et.al., 1978.)

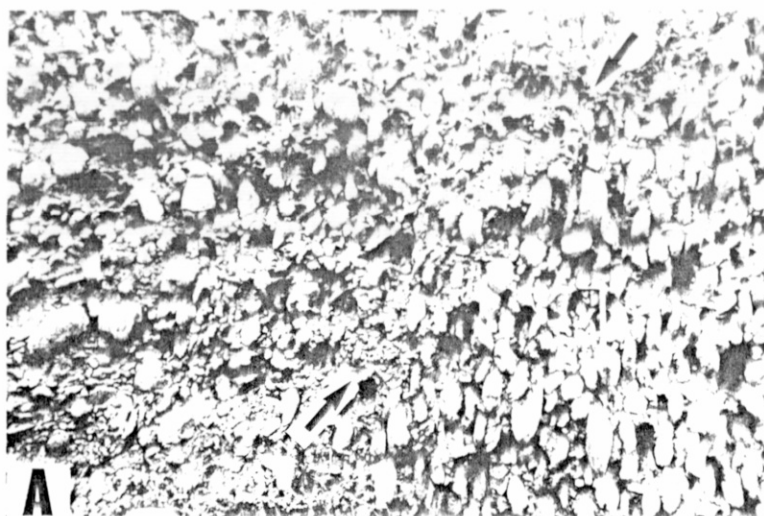
PLATE 2.1 General outcrop appearance of pebble unit.

A. Roadcut appearance of quartzite conglomerate. Bedding dips in the direction of black arrows, and there is a fairly strong alignment of pebble long axes in the dip-direction. Note the differential weathering between clasts and matrix, which often enables the reliable determination of 3-D packing configurations. Hammer for scale.

B. A more detailed view of a typical pebble outcrop. From this range, fractures radiating from points of impingement can be easily picked out; arrows isolate two such contact points. In this photograph, an apparent preferred orientation of fracture planes is evident, running diagonally across photo. Lens cap for scale.

C. Illustration of the unstable nature of many roadcuts. Due to the mechanical weakness of the matrix material, heavy rains create widespread slope instabilities.

PLATE 2.1



variation is systematic. Corrales et.al. (1971) attribute these variations to rhythmic sedimentation within the alluvial fan environment. Table 2.1 summarizes the main sedimentary features of the Mieres conglomerate. It should be noted that both sedimentological and structural features of the Mieres unit are strikingly similar to a set of quartzite conglomerates described by Wiltschko and Sutton (1982) from a Tertiary basin in western Wyoming, USA. In the description of structural characteristics which follows, relevant comparisons will be duly noted.

2.2.2 DESCRIPTION OF PEBBLE DEFORMATION

The most spectacular structural feature of the conglomerate unit is the development of a pervasive set of mesoscopic fractures which radiate from points of impingement between individual pebbles. Plate 2.1B illustrates the typical fracture configuration observed. Since the salient deformational features at the outcrop scale are virtually identical to those described by Wiltschko and Sutton (1982) for the Pass Peak, Wyoming pebble conglomerate, much of their terminology will be repeated here.

Nature of Contacts

Each individual pebble is in point contact with a group of surrounding pebbles, the exact number of which is determined by local packing characteristics. In some cases, contact points are marked by regions of surface abrasion, presumably produced by some form of grinding process. All pebbles show at least two contact marks, and larger pebbles contain many more. In many circumstances one pebble appreciably interpenetrates another; examination of many such interlocked pairs shows that in all cases the geometry of one pebble remains relatively undistorted, while the second develops a marked zone of concavity. In almost all areas where interconnected networks of pebbles were studied in-situ, it was possible to demonstrate that contact pits

UNIT THICKNESS	Approx. 800 M.
PEBBLE COMPOSITION	95% quartz, with the remainder comprised of detrital micas and pore-filling clay minerals.
AVERAGE PEBBLE SIZE	Approx. 10 cm.
MAXIMUM PEBBLE SIZE	Approx. 40 cm.
DEGREE OF ROUNDNESS	Axial aspect ratio (long/short) ranges from 1.0-2.6, with an overall mean of 1.65. (from Corrales et. al., 1971)
SORTING	Highly variable, depending upon location within vertical sequence.

TABLE 2.1. Summary of sedimentological features of the Mieres conglomerate.

and marks were products of pebble-pebble interaction, and that they contained high concentrations of impingement fractures. All field evidence supports the conclusion that the pebbles arrived in place both unmarked and unfractured, and that fracturing occurred in response to syn- or post-depositional stresses.

McEwan (1978) initially examined several groups of pebble conglomerates (including examples from the Mieres conglomerate) as part of a study into pressure solution processes in naturally deformed rocks. He interprets the contact pits as diffusional mass transfer phenomena and shows that contact zones within predominantly monomineralic pebbles are characterized by the following features:

1. Where volume loss between pebbles occurs, insoluble residue (illite, montmorillonite, kaolinite, quartz fragments, iron oxides, and organic remains) accumulates, and the amount of residue deposited is directly proportional to the measured volume loss.
2. The width of the pebble contact, and thus the radius of curvature of the indenting pebble, determines the rate of pebble pitting.
3. Rotation between pebbles during deformation is common.
4. Microcracking within quartz pebbles occurs in the vicinity of contacts; crack widths range up to 5µm, and the cracks were presumably nucleated early in the solution process when stress concentrations were greatest.

From these considerations, it seems clear that the size of individual pits will be influenced by both the overall applied stress level and the initial stress concentration, but pit depth or width cannot be taken as independent measures of the degree of deformation within a given pebble. The fact that solution processes are operating indicates

that stress gradients will be continually modified in response to diffusional mechanisms. The mechanical implications of this interplay between diffusional mass transfer mechanisms and fracture processes will be discussed in section 2.4.2.

Nature of Impingement Fractures

Wiltischko and Sutton (1982) classified fractures from the Pass Peak pebbles into three overlapping groups, based on the degree of observed deformation. The classification appears to apply equally well to the pebbles of the Mieres conglomerate, and the distinguishing characteristics are thus summarized here.

Group 1. - Pebbles show destruction of surface polish at contact marks. Fractures within pebbles appear randomly oriented and evenly distributed. Most fractures are short (<10% of pebble length) and terminate within the pebble interior.

Group 2. - Pebbles show well developed contact marks, and a large degree of fracturing. Contact marks appear slightly lighter in color to the rest of the pebble. The length of major internal fractures commonly ranges from 25% to the whole of the entire pebble, while shorter fractures change direction often and either connect major fractures or branch into finer fracture networks. Long fractures are generally straight, occur in sub-parallel bundles, and commonly connect contact points. Morphological considerations suggest that larger fractures are not generally products of coalescence of smaller individual fractures.

Group 3. - Major fractures run the length of a single pebble or terminate at another fracture. Bundles of parallel crack networks connect contact marks, and fragmentation of the quartzite occurs in the immediate vicinity of contacts. The contact

pits exhibit considerable crushing, and a system of conically-shaped fractures run inward from the outer edges of the pebble pits.

While the above classification characterizes mesoscopic aspects of deformation reasonably well, it partially masks complications which arise from differences in microscopic failure behavior. For this reason, microstructural aspects of pebble deformation are considered in considerable detail in chapter 4. In the remainder of this chapter, aspects of deformation directly observable at the field scale will be considered. At this level of observation, the intensity and orientation of impingement fractures appear to be dominantly controlled by the nature of individual contacts. In the following section, a range of contact geometries will be described, and the fracture patterns observed will be compared with the results of both analytical and experimental studies of the state of stress within granular aggregates. It should be emphasized that these interpretations depend upon the treatment of each pebble as a single particle, and that behaviour within each pebble will be independent of the small scale microstructure. The validity of that assumption will be questioned in chapter 4, but in general, the continuum treatment of individual pebbles appears to hold for observations made at the outcrop scale.

2.2.3 MESOSCOPIC FRACTURE GEOMETRY

As previously noted, fracturing at points of pebble impingement represents the most striking structural feature of the Mieres conglomerate. The Cantabrian zone contains numerous individual groups of Westphalian synorogenic deposits, but deformation within these usually occurs in the form of long transgranular fractures, which maintain a fairly constant orientation as they transect individual clasts. Quite clearly, the mechanical behavior of the two types of conglomerate is fundamentally different; a preliminary discussion of some pioneering studies of aggregate behavior in the field of experimental rock

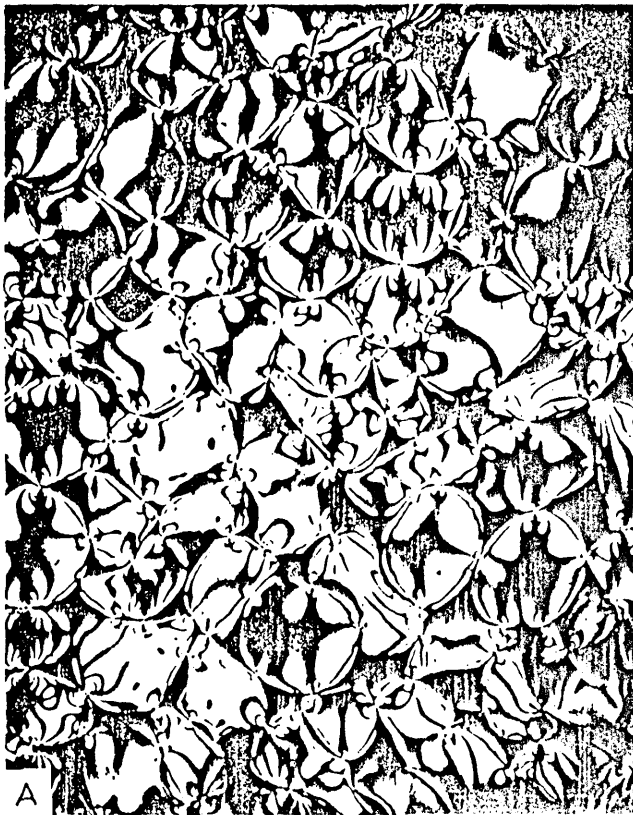
deformation will serve to examine the nature of that difference.

Transgranular vs. Intragranular Fractures

The main rationale for considering individual pebbles as single continua stems from a desire to treat them as large scale analogs of individual quartz grains, for the purpose of comparison with rock deformation experiments in sandstones. In a series of experiments using photoelastic models, glass beads, and unconsolidated quartz grains, Gallagher et. al.(1974) examined the relationship between cement properties and crack behavior in granular aggregates. They showed that the state of stress within individual grains in an uncemented aggregate is controlled by the manner in which the applied load is transmitted at contact points between individual grains. Photoelastic studies showed that strong stress concentrations commonly occur at points of contact, and that different contact geometries exhibit varying degrees of stress concentration. Figure 2.4 shows the results of one of these experiments; an uncemented group of elements of Columbia resin (a common photoelastic material), shaped to simulate sand grains, is loaded by a pair of parallel plattens. Figure 2.4A shows the resultant isoclinics (lines of equal orientation of principal stresses), and figure 2.4B the corresponding isochromatics (lines of equal magnitude of maximum stress difference). Stress intensity concentration is clearly heterogeneous, as evidenced by the varying degree of isochromatic density in different grains. Nonetheless, the number of fringes connecting contact points is greatest in an orientation parallel to the direction of applied load, and falls away at angles to the direction of maximum applied stress.

As part of the same study, Gallagher et.al. demonstrate that fractures follow a path which is the locus of the greatest values of maximum stress difference (ie. parallel to the highest order isochromatic fringe), and are thus predominantly of the extension type. Since the isochromatic fringe orders show a preferred orientation parallel to the direction of applied load, the resultant

FIGURE 2.4. Results of a study of stress concentrations in photoelastic elements shaped to simulate rock grains. Discs are randomly packed. (A) Zero-degree isoclinics, as photographed in plane light, illustrate orientations of maximum principal stress within grains. (B) Isochromatics, as photographed in circularly-polarized light, illustrate variations in maximum stress difference within grains. (After Gallagher et.al., 1974).



fractures should exhibit the same degree of preferred orientation, although the exact range and distribution of orientations will depend upon the nature of the contacts.

When aggregates are cemented, the results are markedly different. Stress concentrations exist, but are located at the center of individual grains. Concentrations at contacts are of very low magnitude. Microfracture patterns are predicted by assuming that orientations depend strongly on the direction of applied load, and that fractures propagate in a direction that is parallel to the greatest principal stress trajectory in regions where maximum stress differences are highest. If the corresponding fractures are also extensional, they should show a high degree of preferred orientation, in a trend that follows the mean orientation of fractures in uncemented grains.

All natural sandstones commonly show some degree of cementation. Nonetheless, the two sets of experiments by Gallagher et. al. (1974) can be viewed as end members in a continuum which incorporates all degrees of cementation. While not an impeccable measure of the degree of cementation in a rock, it is generally true that low porosity sands are more strongly cemented than high porosity sands, particularly after the early stages of deformation when grain boundaries are preferentially broken. Dunn et. al. (1973) performed a series of brittle fracture tests on sandstone cores whose porosities varied from 2% to 24%. Their results clearly demonstrate that in low porosity samples, intragranular extension cracks only develop in the vicinity of throughgoing fault zones. In the very porous specimens, intragranular extension cracks were much more widely distributed, and exhibited a range of orientations similar to that predicted by Gallagher et.al. on the basis of their photoelastic studies.

Applying the results of the preceding discussion to the Mieres conglomerates, I reach the conclusion that deformation within the unit must have occurred when the pebbles were either uncemented or very weakly cemented together. Since the mesofractures are clearly stress induced, I also expect them to show a degree of preferred orientation similar to that predicted by Gallagher et.al.. The next,

chapter presents the results of an attempt to test the validity of that assumption. In the remainder of this chapter actual crack geometries within individual pebbles will be related to their load configuration, stress solutions for point contact geometries will be reviewed, and the degree to which predictions of fracture behavior correspond to natural examples will be assessed.

2.3 DEFORMATION CHARACTERISTICS WITHIN PEBBLE AGGREGATES

The geometry of a given packing configuration strongly influences both the size and distribution of contacts within an aggregate material. Because stress concentrations at intragranular contacts play a fundamental role in determining the mechanical response of an uncemented aggregate subjected to an applied load, a knowledge of the relationship between packing geometry and the corresponding fracture networks is important. The degree to which parameters such as grain size, sphericity, and sorting influence the mechanical behavior of an aggregate is a subject which has been left largely unexplored in the rock deformation literature, although results of rock deformation experiments performed using rocks with a range of initial microstructures (Hoshino et.al.,1972) suggest that a large set of sedimentological variables may affect the brittle response of rocks deformed at shallow depths in the earth's crust. The Mieres conglomerate provides an ideal laboratory for the study of these interrelationships, at a scale which allows direct visual observation.

Ideally, packing configurations should be studied in three dimensions, since the behavior of fractures and cracks out of the plane of section is a subject which has produced much speculation (see Kranz, 1984) but little direct evidence. It was hoped that careful examination of a volume of pebbles would allow a detailed three dimensional analysis. Unfortunately, roadcuts tended to become very unstable when samples were extracted (Plate 2.1C). Because preferential erosion of matrix with respect to pebbles occurs, however, the pebbles have a tendency to stand out; in many cases this is sufficient to enable accurate

determination of fracture trends and pebble depths. Consequently the detailed study of roadcut sections enables a reasonable determination of the spatial relationships between groups of pebbles and the fractures they contain.

In general, impingement fractures within pebbles were not visible from distances at which photography of a large set is possible. For this reason, 2-dimensional "fracture maps" of portions of 2 roadcuts were prepared, at the localities of Ablana and Olloniego. The aim of this study was the determination of mean fracture trends; it had the added advantage of directly relating a set of impingement fractures with the contact geometry which produced them. Plates 2.2A,B show photographs of the mapped section areas at Ablana and Olloniego respectively, and Figures 2.5A,B are the associated sketch maps. Several important conclusions are presented from the mapping study:

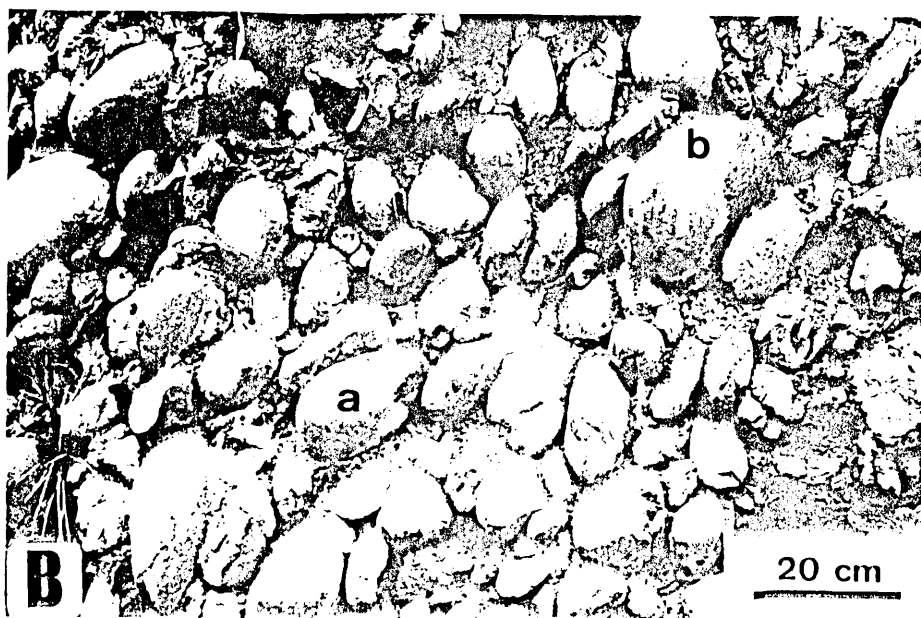
1. No consistent relationship was observed between packing configurations and crack networks. In some sets small, tightly packed pebbles, often enclosed by a "shell" of larger pebbles, produce the highest concentration of fracturing. Elsewhere, suitably oriented larger boulders support most of the overall load.
2. Impingements between two pebbles which are in contact over much of their lengths do contain radiating fractures, despite the fact that the large surface area of contact reduces the stress concentrating effects. Generally, however, a curvature mismatch occurs at these interfaces, which might be an important stress concentrator prior to the development of solution pitting. Where they are in smooth contact, little fracturing is observed.
3. Fracture trends exhibit no signs of the effect of bedding-induced anisotropy due to alignment of pebble axes in the bedding plane, though this behavior is often associated with deformation in unconsolidated sands (Arthur and Menzies, 1972;

PLATE 2.2 Photographs of areas from which fracture maps
shown in fig. 2.5 were prepared. Scale as indicated.

A. Ablana locality.

B. Olloniego locality.

PLATE 2.2



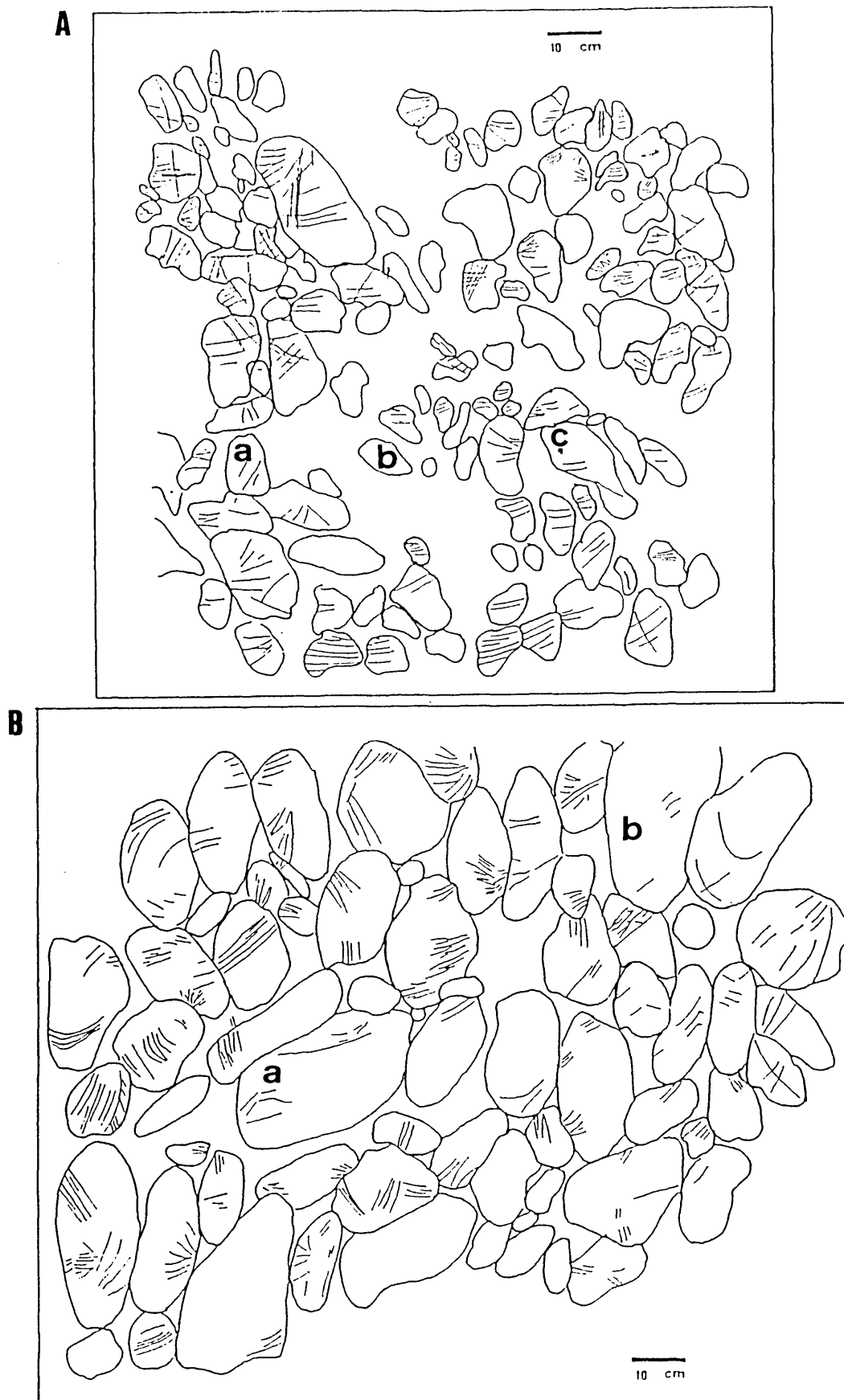


FIGURE 2.5. Detailed impingement fracture maps prepared from field sketches of the roadcut sections shown in Plate 2.2. (A) Ablana. (B) Olloniego.

Yamada and Ishihara, 1979). Small pebbles are widely interspersed throughout the aggregate network, and they provide a proportion of point concentrations which is high enough to ensure that fractures develop with a preferred orientation that reflects the orientation of the principal stress tensor.

4. Where two large pebbles are separated by a smaller pebble, fractures occur in all three, but the smallest pebble generally exhibits the highest fracture density.

These observations generally support the notion that sedimentological shape variables affect mechanical behavior in uncemented rock aggregates. The degree of sorting, in particular, influences fracture trends by controlling the distribution of point contacts. Poorly sorted samples would generally be expected to show a stronger preferred orientation than samples with more equant clast sizes, because they contain a greater number of contact marks per unit volume for the same mean grain size. In a thorough, detailed study, quantitative assessments of these interrelationships might reveal correlations between a host of structural and sedimentological variables.

2.4.1 IMPINGEMENT FRACTURE THEORY

The observations discussed in the previous section suggest that stress concentrations at contacts are controlled by a range of factors which include the area of individual contacts, the number of contacts on a given pebble, and the relative size of impinging particles. To some extent, these factors have been explored within the materials science literature, in the field of indentation fracture mechanics (Lawn and Wilshaw, 1975; Lawn and Swain, 1975). In addition, McEwan (1981) performed a series of photoelastic experiments designed to examine stress distributions within pairs of particles which interpenetrate. The results of these studies help to assess

the way in which applied stress is distributed and transmitted across contacts.

2.4.2 STRESS FIELDS

2.4.2.1 Hertzian Indenter

The shape of a given indenter plays an important role in determining the stress boundary conditions in contact zones. Hertz (1881) examined the nature of the stress field which results from loading a flat surface with a spherical indenter, and Lawn and Wilshaw (1975) describe the main characteristics of the ideal Hertzian field, as follows. A linear elastic half space is subjected to normal loading by a sphere of radius r . If E and E' are taken as the Young's moduli and ν and ν' as the Poisson ratios of specimen and sphere respectively, then three equations are sufficient to specify the loading conditions for any common indenter arrangement. The radius a of the circular elastic contact is given by

$$a^3 = 4kPr/3E \quad (1)$$

where P is the applied normal load and k is a dimensionless constant ,

$$k = 9[(1-\nu'^2) + (1-\nu^2)E/E'] \quad (2)$$

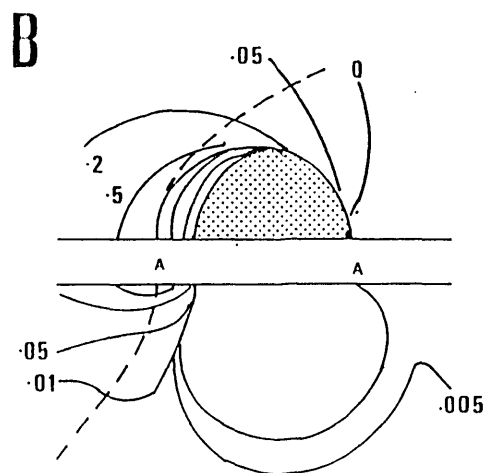
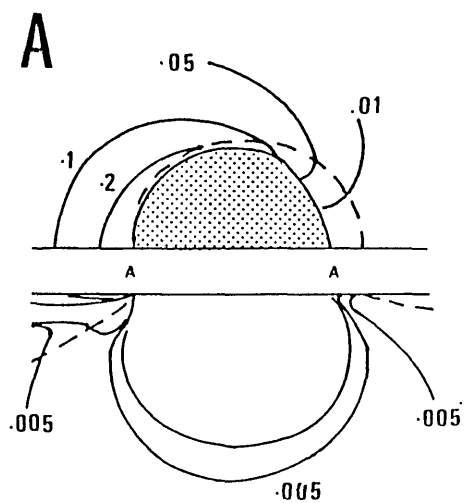
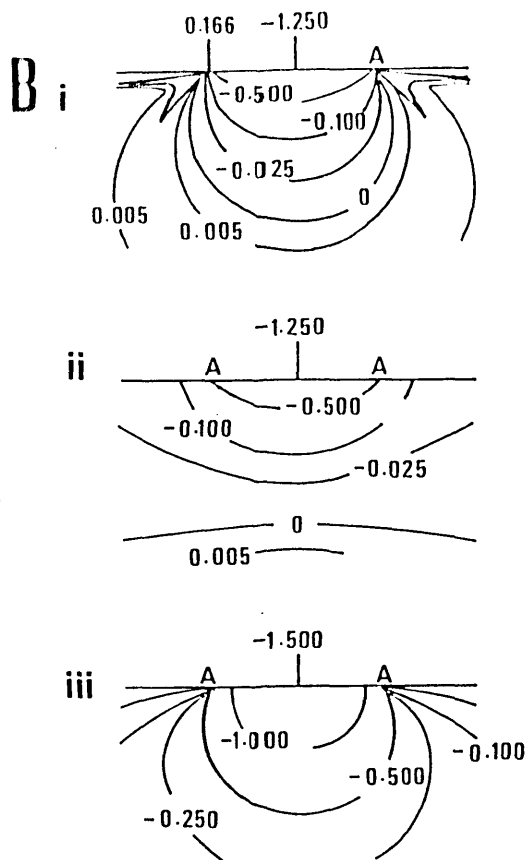
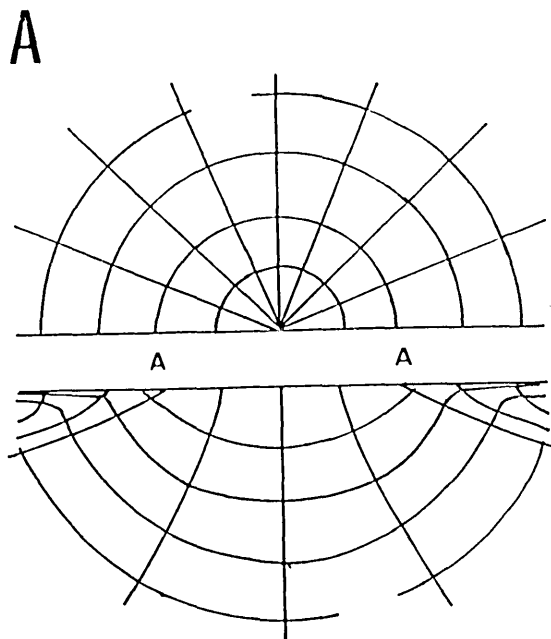
The distance of mutual approach , Z , between contacting bodies is given by

$$Z^3 = (4k/3E)^{2/3} P^2 / r \quad (3)$$

Figure 2.6A shows the resultant stress trajectories of the Hertzian field, with the associated contours of principal normal stress drawn in Figure 2.6B. Maximum tensile stress occurs at the edge of the contact area and is radially directed, falling off with radial distance p from the contact circle according to

FIGURE 2.6. Stress fields associated with Hertzian indent configuration. (A) Half-surface view (top) and side view (bottom) of principal stress trajectories, plotted for a value of Poisson's ratio, $\nu = 0.33$. AA denotes area of contact. (B) Contours of principal normal stresses, (i) σ_{11} , (ii) σ_{22} , (iii) σ_{33} , in Hertzian field, shown in the plane which contains the contact axis. Contours are plotted for $\nu = 0.33$, unit of stress is p_0 (applied load), contact diameter AA is $2a$. (After Lawn and Wilshaw, 1975).

FIGURE 2.7. Half surface view (top) and side view (bottom) of greatest principal stress in elastic specimen in contact with sliding sphere (motion is left to right). (A) Coefficient of static friction, f , = 0.1. (B) $f = 0.5$. Unit of stress is p_0 , and dashed lines are (surface view) and (side view) drawn from the position of maximum tensile stress in the specimen. $\nu = 0.33$. (After Hamilton and Goodman, 1966).



$$\sigma_{pp}/p_0 = (1-2\nu/2)(a/p)^2, (p \gg a) \quad (4)$$

The most significant conclusions one can draw from the resultant stress field are:

1. Extremely high stress concentrations form at the edge of the contact zone.
2. Gradients are most severe for small contact areas.

In practical situations, force is rarely applied exactly normal to the specimen surface. Where tangential forces arise at the interface due to lateral motion between indenter and sphere (a situation which undoubtedly occurs at pebble contacts), substantial modifications to the stress field will arise. Hamilton and Goodman (1966) provide complete stress solutions for this situation for a range of values of f , the coefficient of kinetic friction. These are shown in figure 2.7. With respect to the ideal Hertzian field, two chief differences are noted:

1. Behind the indenter, tensional forces are dramatically enhanced, whereas ahead of the indenter's path, tensions are greatly suppressed.
2. There is a reduction in stress gradient below the trailing edge of the moving sphere, as well as a marked deviation away from the axial symmetry of the Hertzian field.

2.4.2.2 Interpenetrating Contact

As the geometrical boundary conditions associated with a given contact deviate from symmetric configurations, exact stress solutions become intractable. In his study of the brittle behavior of pebble conglomerates which show a degree of interpenetration, McEwan (1981) performed a series

of photoelastic experiments designed to semi-quantitatively demonstrate the effects of increasing the area of contact between surfaces. A photoelastic disc 7.5cm in diameter was loaded against a set of 6 rectangular blocks. Out of each block, a circular segment corresponding to a pressure solution pit at different stages of development was cut. Isochromatics and isoclinics (see section 2.2.3.1) were used to study stress trajectories and potential shear planes in the indented surface.

Figures 2.8 and 2.9A summarize the model results. In figure 2.8A the isochromatic fringe patterns for three stages of indentation are drawn. Clearly, the location of stress maxima shifts to the contact boundaries as indentation proceeds, until a critical contact area is reached. At this point, the maxima return to the center of the contact area, but the gradient decreases in both contacting bodies. These distributions are used to calculate the trajectories of potential shear planes (assuming an angle of internal friction of 30 degrees), as shown in figure 2.8B. In figure 2.8C trajectories of σ_1 are drawn (dashed lines); these represent potential paths for mode I extension fractures. They are compared with trajectories of σ_n (solid lines), drawn normal to the curvature of contact between the two bodies. The diagram illustrates the fact that while the two sets of trajectories deviate away from the center of the contact area, they are generally subparallel over the central part of the pit. Extension fractures will presumably form within a small angle (generally < 30 degrees) of the normal to the center of the pit, a fact which McEwan confirms with orientation measurements from a set of deformed pebbles in the French Alps.

Figure 2.9A(1) is a plot of several independent measures of stress (see figure caption for descriptions) versus contact area. The curve defined by a set of open squares is a plot of maximum principal stress difference vs. contact area. The curve is compared with calculated results of mean and maximum compressive stress, which were determined assuming a constant stress over the contact surface, and a maximum compressive stress equal to 1.5 times

FIGURE 2.8. Stress fields associated with interpenetrating contact configuration.

A. Isochromatics (lines of maximum principal stress difference) found from loading photoelastic disc against (a) a plane surface, (b) a circular cut-out of .635cm depth, and (c) a circular cut-out of 2.54 cm depth.

B. Potential shear planes developed for six different load configurations of increasing cut-out depth, assuming an angle of internal friction (φ) = 30 degrees.

C. Trajectories of σ_1 (dashed lines) and σ_n (solid lines) for the six loading configurations, as in B.

(After McEwan, 1981)

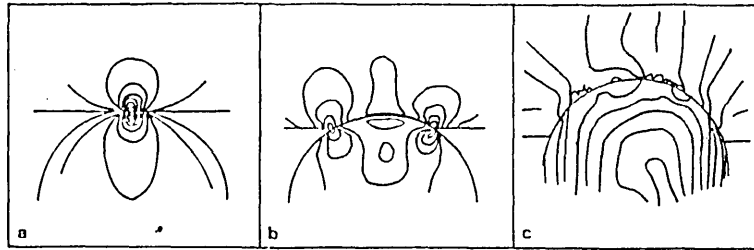
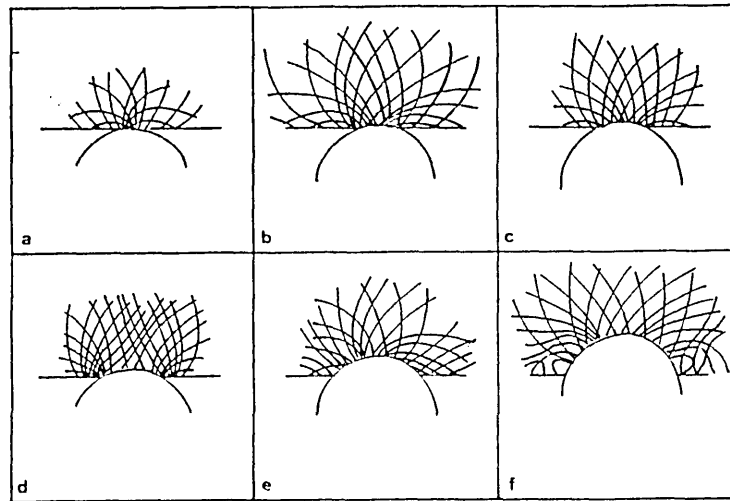
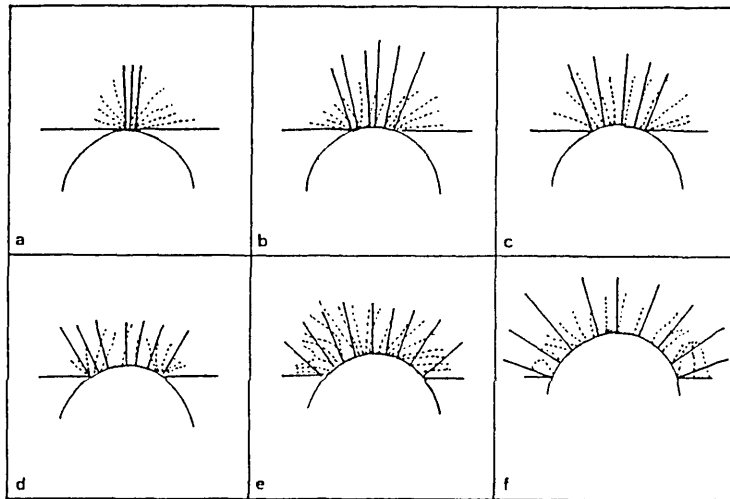
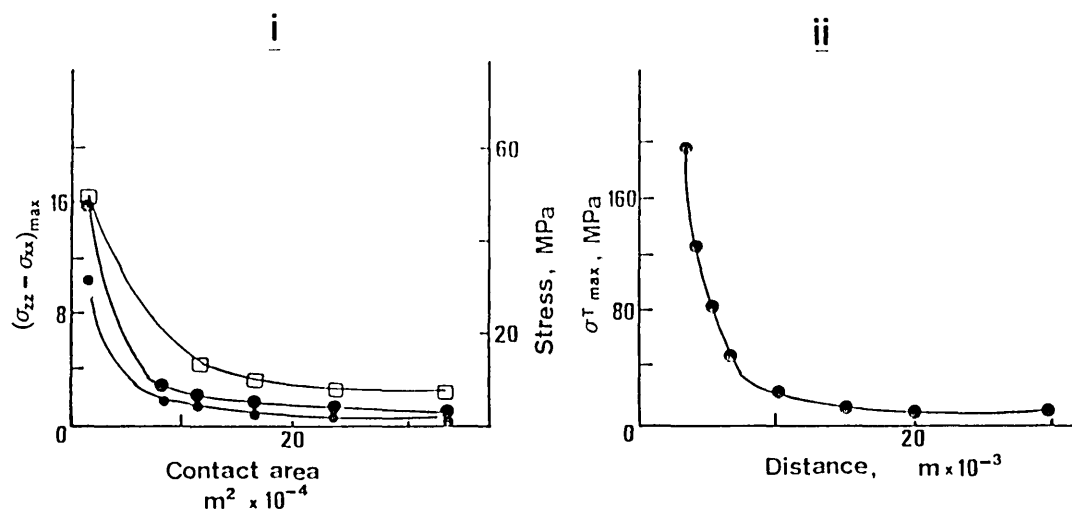
A**B****C**

FIGURE 2.9 (A) Stress/contact area relationships for different indenter configurations. (i) The maximum isochromatic fringe order (squares), maximum compressive stress on contact (large dots), and mean compressive stress on the contact (small dots) plotted against the contact area between the disc and block of figure 2.8. (ii) The value of maximum principal stress in the surface region of a planar surface (i.e. spherical indenter penetrating elastic half-space) with the same elastic constants as the indenter, due to Hertzian loading (indenter radius = 0.005m , $E = 5.5 \times 10^4 \text{ MPa}$, $\nu = 0.25$) with a load of 250kg ; plotted against the distance from the contact center. Calculated from Hertz (1881).

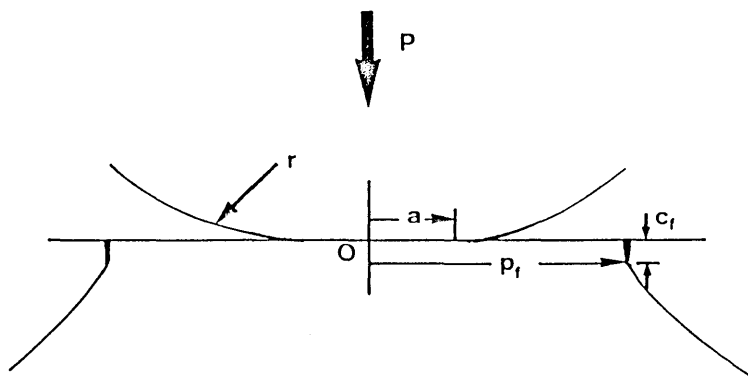
FIGURE 2.9B. Parameters for Hertzian cone crack configuration. P = applied load, a = contact radius, P_r = surface location of initial flaw, c_r = initial flaw length, and r = radius of indenting sphere. (After Lawn and Wilshaw, 1975).

FIGURE 2.9C. Parameters of Roesler cone crack configuration. R_0 = contact radius, R = radius of well-developed cone, and P = applied load. (After Roesler, 1956).

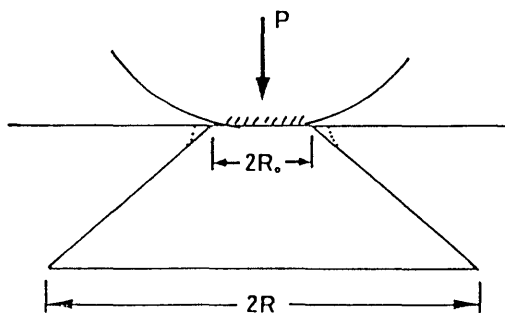
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C



the mean value. Figure 2.9A(11) is a plot of maximum tensile stress vs. contact area, as calculated from the Hertzian equations. Both plots show a marked decrease in their respective stress measures with an increase in contact area.

2.4.3 MECHANICS OF FRACTURE

Having described the stress field associated with a given indent configuration, it is necessary to further characterize fracture formation by identifying the mechanism by which a crack nucleates (the initiation stage), as well as the path it will follow once started (the propagation stage). Lawn and Wilshaw (1975) present a complete review of indentation fracture theory, and relevant aspects will be summarized here.

The propagation stage is of particular interest in the study of pebble fracture, since it is observed that fractures commonly terminate within a given pebble. A quantification of the factors which control fracture arrest is especially desirable, since energy balance considerations suggest that propagation is generally a "stable" phenomena; i.e. fracture length is directly related to the magnitude of applied load for the case of a spherical indenter. If this principle holds true in rocks which deform by indentation processes, it might be possible to utilize crack data to obtain rough estimates of the stress magnitudes required to initiate failure.

2.4.3.1 Crack Initiation

A given fracture mechanics analysis assumes a knowledge of the prospective crack geometry, which appears as the stress intensity factor in analytical equations. In polycrystalline materials, it is assumed that initiation begins from "flaws" (pores or micron -scale microcracks), which upon achieving some critical length, become "dominant" and develop into discrete propagating cracks. The probable

location of a favorable starting flaw is determined by the indentation stress field, and it seems reasonable to assume that cracks will initiate in regions of highest tensile stresses (i.e. at the contact surface or along the applied load axis). Lindqvist et.al. (1984) document nucleation arising in both areas during a series of indentation tests on a variety of rock types, which were directly observed under the SEM. It should be noted that inelastic deformation at singular points (i.e. dislocation "pile-ups") may cause nucleation of new flaws in favored locations. Regardless of the physical nature of the nucleation point, however, it is relatively safe to assume that initiation will occur in a location which is controlled by the tensile stress field associated with indentation.

2.4.3.2 Propagation

The propagation stage of crack formation is considerably more amenable to quantitative analysis. The applied loading system is the only driving force, and the extension path is derived from the familiar Griffith energy balance concept. The tendency for a "well-developed" crack (a crack which outgrows the influence of its nucleating forces) to continue extending is governed by a thermodynamic budget of the form

$$U = (-W_L + U_E) + U_S \quad (5)$$

where U is the total energy of the system, W_L is the work done by the applied forces, U_E is the elastic strain energy in the cracked body, and U_S is the total surface energy of the crack. In applying the "fracture mechanics" formulation, the variation in these energy terms is considered with respect to crack area C ,

$$dU/dC = d(-W_L + U_E)/dC + dU_S/dC = -G + 2 \quad (6)$$

where G is the mechanical energy release rate and Γ is the fracture surface energy. In an ideal brittle solid, where no energy is dissipated when new surfaces are formed, Γ is

synonymous with γ , the crack surface energy per unit area.

The relative orientation of a given increment of extension will be that which maximizes the quantity $G-2\gamma$; for isotropic solids γ is uniform in all directions, and the extension path is thus governed by a maximization of G alone. Unfortunately, determination of the mechanical energy release rate function is analytically impossible, because of the complex geometries encountered in indentation problems. Nonetheless, by making certain very general assumptions, one can proceed with an approximate analysis.

For the Hertzian field, an explicitly defined crack geometry - the Roesler cone crack - is specified. The parameters of the configuration are shown in figure 2.9B. A starting flaw of effective length c_r , located at a distance p_r from the contact center, experiences a very inhomogeneous, time varying tensile field. For an analysis to be feasible, several approximations concerning subsequent crack growth from that flaw must be made. Specifically, knowledge of the starting point of the crack is supposed, and it is further assumed that the crack is subjected to plane strain conditions, and will exactly follow the indentation stress trajectories.

Crack growth is subsequently modeled in two stages. Roesler derived an expression for the mechanical energy release rate function of the form

$$G = k(\nu)P^2 / ER^3 \quad (R \gg R_0) \quad (7)$$

Where R_0 and R are the radii of contact area and growing cone respectively (see fig. 2.9C), $k(\nu)$ is a dimensionless function of poisson's ratio, E is Young's modulus, and P is the applied load. It should be stressed that the relationship is derived for crack growth in a vacuum, and the relationships cannot be directly extrapolated to crack growth which occurs in the complex chemical environments commonly present in naturally deforming systems. Here, kinetic factors briefly discussed in Chapter 1 must be considered. For the purpose of this discussion, it should simply be noted that a crack which is at equilibrium (neither growing or closing) in a vacuum shows a tendency to

resume growth without the application of further load when air is admitted to the system. This observation outlines the difficulties one encounters when attempting to relate the length of a given crack to the magnitude of the load which produced it.

The Roesler expression for the mechanical energy release rate function is not applicable to the early stages of crack growth, when the stress field of the indenter contact is superposed upon the stress field associated with the loaded starting flaw. The mechanical energy release rate function, G , initially takes the form

$$G = P/kr[\varphi(c/a)]_{\sqrt{p_r/a}} \quad (8)$$

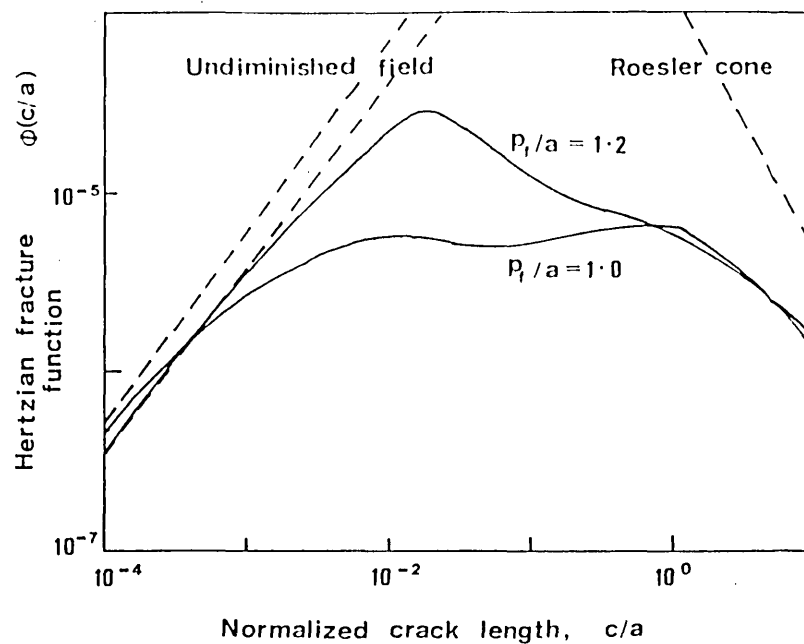
where P , k , and c are defined as previously, and φ is a dimensionless function of a , the radius of contact between sphere and surface, and p_r , the radial distance from the contact center and the starting flaw. φ is generally evaluated numerically. Figure 2.10 shows plots of this function for two different values of p_r/a , and compares the results with the Roesler solution. Quite substantial deviations from the Roesler values occur for normalized crack lengths less than 1. Also, the position of the starting flaw appears to strongly control the value of φ ; note the presence of a "hump" in the $\varphi(c/a)$ curve for $p_r/a = 1.2$, and its absence for lower values of normalized crack length.

Using this more complex near-field expression for G , a sequence of initial propagation can be predicted. The details are omitted for simplicity, but two essential results are noted:

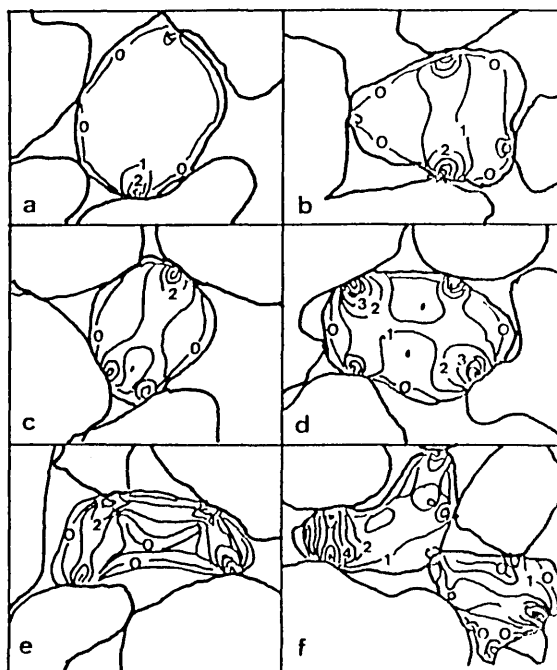
- In a vacuum, 4 stages of growth are predicted. Two stable growth phases, separated by a short period of unstable growth, precede the subsequent formation of a full cone crack. Full cone development proceeds only after the application of some critical load. The value of that load is dependent upon the size of the indenter.

FIGURE 2.10. Plot of mechanical energy release rate function for the case of cone crack formation. Curves are computed for 2 different starting locations at the specimen surface, for flaws which experience inhomogeneous, time-varying stress fields. Also shown are curves corresponding to stress fields undiminished from surface values, and the Roesler expression for a fully-developed cone crack. (After Lawn and Wilshaw, 1975).

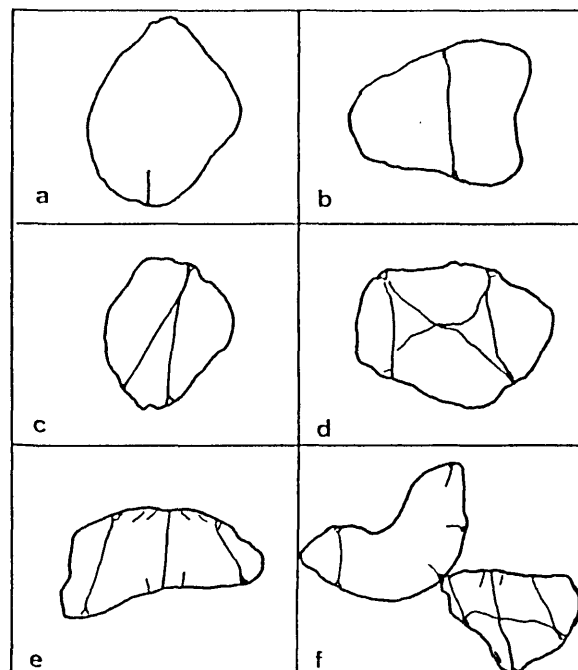
FIGURE 2.11. (A) Isochromatic fringe patterns for naturally-shaped photoelastic discs subjected to a range of load configurations. Dark lines are grain boundaries, and light lines are isochromatic fringes. Six load configurations are illustrated: (a) single load, (b) double load, (c) triple load, (d) quadruple load, (e) beam load, and (f) combined loads. (B) Predicted fracture patterns (internal lines) associated with the loads in (A). (After Gallagher et.al., 1974)



A



B



- Under non-vacuum test conditions, growth occurs in a rate-dependent manner, and is controlled by a reduced, environment-dependent value of fracture surface energy. The critical condition for cone formation is a function of time spent in dynamic growth, which depends upon crack velocity.

2.4.4 MODEL CALCULATIONS

To give the fracture mechanics equations some physical meaning, it is instructive to apply the Roesler solution directly to the problem of pebble fracture. The initiation problem is ignored, since there seems little doubt that initial flaws are sufficiently abundant to allow the growth of well-formed cone fractures. If one assumes that indentation fracture growth proceeded stably, equation (7) should allow one to calculate the force needed to propagate a cone crack across the diameter of a single pebble. While the Roesler solution is derived for a circular punch indenting an infinite half space of elastic material, his experiments show that specimens of moderate size (i.e. centimeter dimensions) give valid results. Boundary effects near specimen edges will have a tendency to cause deviation of the crack path before the cone actually reaches the pebble edges, but as a first approximation these can be overlooked.

From equation (7) we can relate the applied force to crack radius by

$$P^2 = G E R^3 / k(v) \quad \text{for } R \gg R_0 \quad (9)$$

For a spherical pebble 10cm in diameter, the crack radius at failure will range from 3 to 5cm, depending upon the angle of the cone. Contact marks measured in the field have diameters of perhaps 1cm, yielding a ratio of R/R_0 of between 3 and 5. In his experiments, Roesler analysed geometries with R/R_0 ratios of between 3 and 7, and found that the ratios of crack radius to applied force varied by

less than 10% for different sized indenters. Thus, the contact to cone radius ratios determined from pebble observations should be amenable to the cone crack analysis.

Values of the mechanical energy release rate function (G), Young's modulus (E), and poisson's ratio (ν) can be estimated from values obtained for Oughtbridge Gannister, a quartzite which is microstructurally similar to the pebbles of the Mieres conglomerate. Hadizadeh (1980) reported values for poisson's ratio and Young's modulus of .194 and 2.4×10^{10} Pa respectively. G can be calculated from the critical mode I stress intensity factor, K_{Ic} , from the following expression:

$$G_c = K_{Ic}(1 - \nu^2)/E = 2Q_r, \quad (10)$$

where $2Q_r$ is the fracture surface energy. Taking a value of K_{Ic} of $1.35 \pm .2$ MPa $m^{-1/2}$ (Meredith, 1983), we then have:

$$\begin{aligned} G_c &= (1.35)^2 \times (10)^2 \times (1 - (.194)^2) / 2.4 \times 10^{10} \text{ Pa}^2/\text{m} \times \text{Pa} \\ &= 72.9 \text{ Pa/m} = 72.9 \text{ J/m}^2 \end{aligned}$$

It should be emphasized that this is the value of G for catastrophic (i.e. fast) crack propagation. Atkinson (1984) notes that subcritical crack growth commonly occurs at values below K_{Ic} , so that the value of G used here will represent an upper limit bound.

Roesler calculated the value of $k(\nu)$ numerically, and found that for a poisson's ratio of .2, $k = 2.5 \times 10^{-3}$. Combining these values in equation (9), we have

$$\begin{aligned} P^2 &= (72.9)(2.4 \times 10^{10})(.05^3) / 2.5 \times 10^{-3} \text{ Pa}^2\text{m} \\ &= 8.74 \times 10^{11} \text{ N}^2 \end{aligned}$$

$$\text{or } P = 9.3 \times 10^5 \text{ N.}$$

To calculate the resultant stress, force must be divided by the contact area; for $R_p = .5\text{cm}$,

$$= 9.5 \times 10^{-7} / (0.005) \text{ Pa} \times \text{m}^2/\text{m}^2$$

$$= 1.19 \times 10^4 \text{ MPa.}$$

When compared with experimental data on the failure strength of Oughtbridge Gabbro (Hadizadeh and Rutter, 1983), the calculated value seems high by at least a factor of 10. Water saturated specimens deformed under confining pressures of between 0 and 400 MPa were found to have ultimate strengths of between 700 and 1300 MPa. Dry samples showed higher ultimate strengths, but faulted specimens never exhibited strengths greater than 1500 MPa. It seems unlikely that the quartzite which comprises the conglomerate pebbles is anomalously strong, so it is instructive to consider the possible sources of overestimation.:

(1) As previously noted, G has been calculated using the critical stress intensity factor, K_{Ic} . Experimental data from subcritical crack growth studies show that subcritical cracking can occur at values of K_I below K_{Ic} , and Atkinson (1984) notes that cracking may occur at values of stress intensity factor which are 10-20% of the critical value, K_{Ic} . Since both K_{Ic} and P appear as square terms in equation (9), the stress required to break a pebble might be lower than the calculated value by a factor of 4 or 5.

(2) Purely mechanical pore fluid effects may allow the rock to crack at lower differential stresses, particularly if the propagating crack is filled with fluids. Provided strain rates are slow enough to allow pressure equilibrium within the growing crack (thus preventing the dilatancy hardening effects observed by Brace and Martin (1968)), the differential stress required for failure will be governed by an effective stress law of the form:

$$\sigma_{ij} = \sigma_{ij} - \kappa p_{H_2O} \delta_{ij}$$

Where σ_{ij} is the applied stress, k is a constant (which can be taken as 1 if the fluids are fully effective in acting on individual rock grains) and δ_{ij} is Kronecker's delta.

(3) While the assumption that the physical properties of the quartzite pebbles are similar to those of Oughtbridge gannister may be dubious, it seems unlikely that the estimate will produce gross errors. If anything, the value of G obtained for gannister is low when compared to that obtained for other experimentally tested sandstones and quartzites (Atkinson, 1984). Consequently, the calculated force cannot be substantially reduced by assuming much lower fracture toughnesses.

(4) Since the crack radius, R , appears as a cubed term in equation (9), this seems the likeliest source of the discrepancy. If the quantitative treatment is turned around (ie. assume a more reasonable ultimate strength of 1200MPa), one can quickly calculate the maximum radius cone which might be expected to form from a contact 1cm. in diameter. From equation (6), we have:

$$R^3 = k(v)P^2/EG \quad (11)$$

and using the values obtained above we obtain:

$$R^3 = (2.5)[(1.2)(3.14)(.005)^2 \times 10^6]/(2.4)(72.9) \times 10^{10}$$

$$\text{and } R^3 = 1.27 \times 10^{-5} \text{ m}^3$$

$$\text{or } R = 2.3 \text{ cm}$$

2.5 OBSERVED BEHAVIOR: A COMPARISON

Having explored several theoretical predictions of crack geometries based on indentation fracture theories, it remains to compare these predictions with some of the fracture patterns actually observed within the Mieres conglomerate. Plate 2.3A is a close-up view of a typical impingement contact between two equal-sized pebbles, and it illustrates several important features. In an overall sense, the cone crack geometry develops according to Hertzian indent theory; a set of sub-parallel fractures radiates from the contact zone (P) and widens away from that interface. In detail, however, two differences are noted. First, the "crack" develops as a series of closely spaced discontinuities, and not as a single cone. In addition, the set does not propagate with its initial configuration across the entire width of the pebble. Black arrows indicate positions where significant bending of fracture traces occurs. It is interesting to note that this deviation is seen at a value of crack radius equal to approximately 2cm., the maximum expected cone crack radius as calculated in the previous section. Presumably, path deviation occurs in response to the imposed boundary conditions on the pebbles. Initiation and the early stages of propagation will be dominantly influenced by the near-field stress around the nucleating contact, but as a given fracture extends, its direction will also be controlled by the stress field arising from the other contacts of the pebble. In thermodynamic terms, it may be true that the cone crack configuration maximizes the mechanical energy release rate in the near-contact field, but as the fracture propagates further from the contact, a new crack path may become more "energy efficient". Hence, cracks which propagate at a high angle to the pebble long axis early in their growth history may change paths and proceed nearly parallel to that axis as they extend.

The stress field solutions of Hertz and McEwan, which are based upon contacts between a spherical indenter and semi-infinite plate, ignore the effect of neighboring contact fields, but a re-examination of the photoelastic

PLATE 2.3. Detailed views of contact/fracture configurations.

A. Impingement between two equal-sized pebbles (P) produces classic Hertzian cone crack geometry. In detail, the fractured zone contains 4 or 5 discrete surfaces which trend at a constant angle to the contact normal then change direction within the pebble interior (black arrows).

B. Comparison of fracture behavior in zone with poor size sorting. Arrows point to fractures identified as extension ("e") and shear ("s"), as described in text.

PLATE 2.3



aggregate in Gallagher et.al.'s study (fig. 2.4) shows the importance of stress field interference in cases where the ratio of applied load to pebble dimensions is high. They also assessed a range of idealized contact geometries likely to arise in well-sorted, well-rounded aggregates, and proposed a corresponding set of fracture patterns which might be expected to develop according to the extension fracture criterion. These are shown in figure 2.11. Again, fracture geometries as seen in the field often correspond to the general model predictions, but stress is relieved through the formation of dense fracture arrays, and not by the formation of a discrete single surface. The two small pebbles in plate 2.3B are loaded in the diametral configuration of figure 2.11B(b), and the arrow marked "e" points to a network of extension fractures. Formation of a dense fracture set presumably reflects the scale difference between individual quartz grains and pebbles (or laboratory specimens) comprised of a collection of grains. In an individual grain, the formation of one or a few extension cracks might dissipate much of the applied mechanical energy through the formation of new surface energy. In a pebble, the formation of one fracture is presumably insufficient to maintain energy equilibrium as stated in the Griffith energy balance equation. The growth of several fracture surfaces is presumably required to restore equilibrium throughout the volume of the pebble. It would seem that the amount of fracture surface area which must form to restore the energy balance depends upon the volume of the loaded particle, assuming the stress across the contact is constant

Further differences exist between the load-fracture relationships determined by Gallagher et.al. (1974) and those which have evolved in the course of this study. In many pebbles, evidence exists to support the conclusion that (a) individual extension fractures coalesce to form macroscopic shear faults within single pebbles, and (b) rotation between pebbles at contact points initiates shear sliding along fractures which originally developed as mode I type. The large pebble in plate 2.3B contains two surfaces marked "s" which developed with a markedly different orientation to the dominant extensional set within

the pebble ("e"), and displacement was inferred to have occurred out of the plane of the photograph. Plates 2.4B,C illustrate more spectacular examples of the same phenomena. In 2.4B, a brittle shear zone (Ramsay and Graham, 1970) develops in the large pebble; the boundaries of the zone are aligned parallel to the pencil, and a dense set of fractures develops at a high angle to that boundary. In 2.4C, the large pebble is fragmented by a set of conjugate faults whose trends are bisected by a network of fractures running horizontally across the photograph. Both examples show an anomalously intense stress concentration within the affected pebbles, or an anomalously weak response to the applied load.

Evidence for reactivation of mode I extension fractures is based primarily upon microstructural evidence, though certain mesoscopic features are thought to be diagnostic of sliding activity. Plate 2.4A shows a set of pebbles which contains a well-developed fracture network running horizontally across the photograph; marked topographic offsets are apparent on many of the surfaces. It is thought that these result from small but significant displacements along the fractures. Grinding and plucking associated with sliding results in cataclastic size reduction of quartz grains, and this serves to enhance the topographic effect as the faulted surfaces act as effective fluid conduits and become progressively eroded.

One final point should be noted: a fair degree of caution must be exercised when attempting to relate the fracture traces observed in outcrop to the stress field under which they are inferred to have formed. Figure 2.12 shows hand tracings of fracture patterns observed on planar cuts through individual pebbles. In detail, the patterns are highly complex and reflect a marked degree of interaction between fractures. The patterns are particularly varied near pebble edges, which may indicate that sliding along contacts initiates a range of orientations of small cracks which develop in response to the changing stress field (recall fig. 2.7). In chapter 4 it will be shown that, at still smaller scales, a range of microstructural variables influence the geometries of crack configurations. The

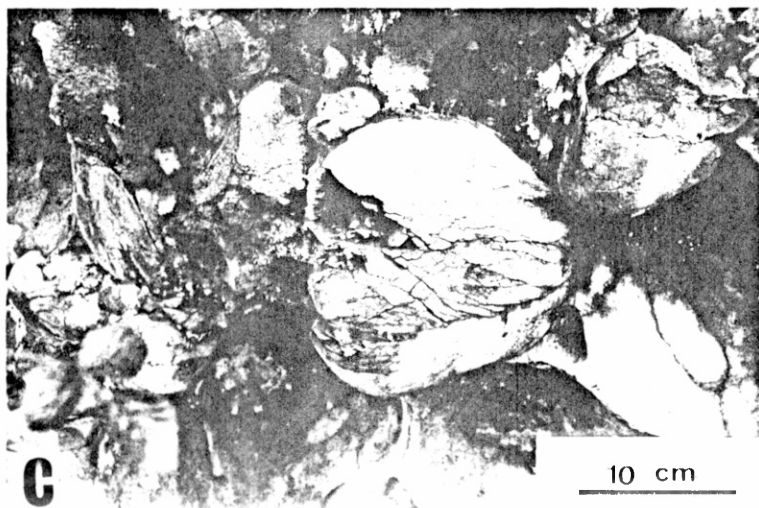
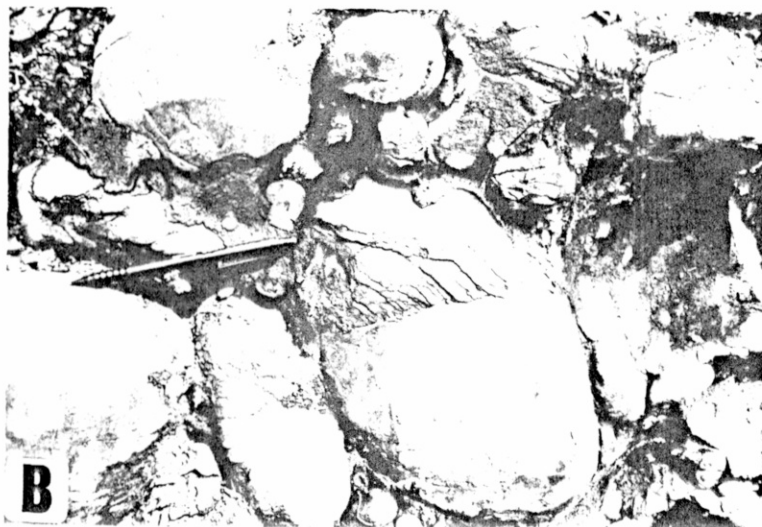
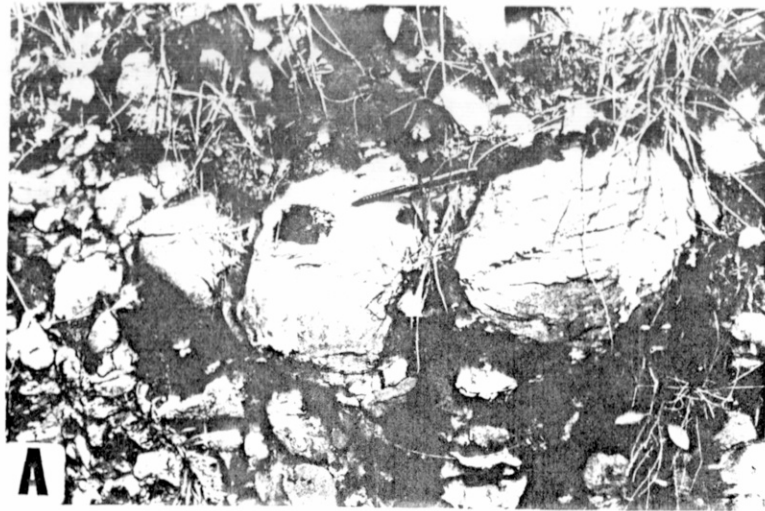
PLATE 2.4

A. A set of contacting pebbles contains a group of sub-horizontally aligned fracture traces, displaying visible topographic offsets. Surfaces are thought to have originated as extension fractures, along which subsequent sliding has taken place.

B. "Brittle shear zone" similar to those described by Ramsay and Graham (1970). Boundaries of zone are aligned parallel to pencil, and a set of curvilinear traces trends at a high angle to this boundary.

C. Fragmentation of a pebble along a set of conjugate fractures. "Pie-shaped" slice within densely fractured pebble picks out two dominant fracture trends.

PLATE 2.4



combination of these factors serves to limit the extent to which a given fracture set can be interpreted solely in terms of its packing geometry.

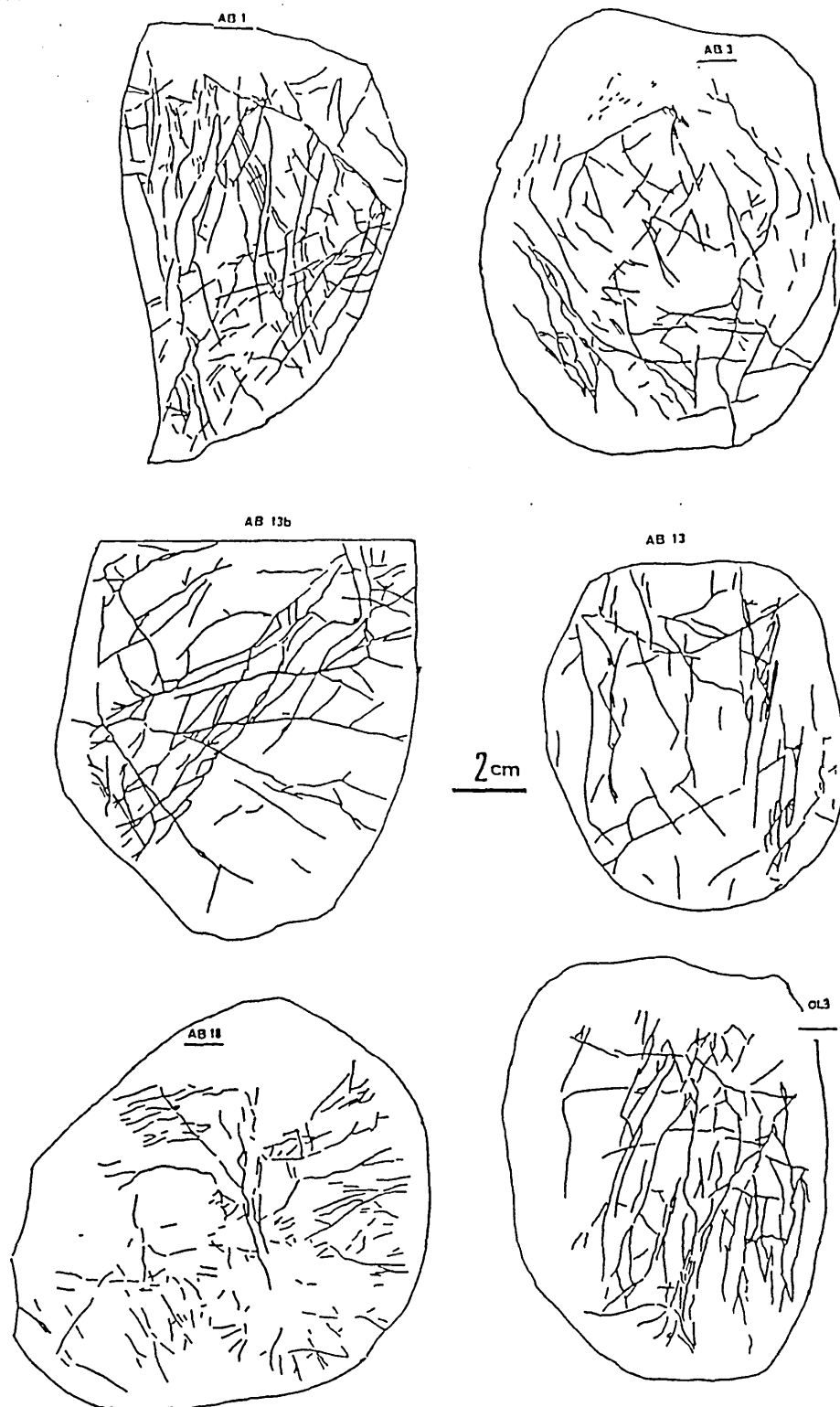


FIGURE 2.12. Detailed crack tracings from planar cuts through six pebble surfaces, illustrating the pervasive extent of internal cracking and complexity of patterns produced. Note especially the non-uniformity of crack orientations around pebble edges.

Chapter 3

CRACK AND FRACTURE ORIENTATION STATISTICS

3.1 INTRODUCTION

Careful scrutiny of either of the meso-scale fracture maps in Chapter 2 seems to suggest that, on the scale of individual exposures, the impingement fractures develop with a strong degree of preferred orientation (see plates 2.1B and 2.4A as examples). In the previous chapter I discussed the degree to which single pebbles could be treated as large scale analogs of quartz grains. This being the case, development of preferred alignment of fractures should be expected, assuming that the pebbles failed in response to a load with a component of differential stress; numerous experimentalists have noted the tendency for intragranular microcracks to align within 30° of the direction (e.g. Gallagher et.al., 1974; Conrad and Friedman, 1976) during triaxial tests. Recently, Blenkinsop and Rutter (1985) have studied cataclastically deformed rocks from the Moine Thrust Zone in NW Scotland, and report a similar tendency for naturally formed extension microcracks to show a strong preferred orientation. It was hoped that by measuring fracture orientations within the conglomerate, the extent to which deformation in the pebbles mimicked that seen in smaller scale studies could be ascertained. Determination of mean fracture orientations might then prove useful in assessing the nature of the load that produced the observed deformation.

The study of fractures is very much a scale-dependent process, since the magnification at which structures are viewed profoundly influences exactly what one sees. For this reason, impingement fractures within the Mieres conglomerate were measured at individual outcrops with a compass/clinometer, and thin sections were then prepared and subjected to closer scrutiny using a combination of optical and scanning electron microscopy

techniques. In this way, orientation data collected in the field provided the areal coverage needed to assess the nature of the stress field along strike of the conglomerate unit (i.e. its uniformity or lack thereof), and data obtained from a more limited number of oriented specimens was used to relate microstructural characteristics to the meso-scale observations.

The chapter is divided into two sections. In the first, 3-dimensional orientation results are presented based on direct field observation. The second section describes a method of studying 2-dimensional surfaces with the aid of a hand-digitizing pad and microcomputer, and relates the results determined with this technique to those obtained in section 3.2.

3.2 FIELD MEASUREMENTS

3.2.1 Method of Analysis

In most cases, preferential erosion of matrix with respect to clasts in a given roadcut allowed for 3-dimensional measurements on a single layer of exposed pebbles. The general method of measurement involved identifying fractures initiated at contact points, assessing their trend as nearly as possible by following the fracture trace on the exposed pebble surface, and measuring the strike and dip of the inferred plane with a compass/clinometer. Fractures often occur in sets which radiate from contact marks; where this configuration was observed, the mean trend of that set was measured. Where 3 or 4 fractures run as parallel sets across a pebble, one measurement was taken to represent the set. To minimize statistical bias, measurements were made on roadcut faces oriented at right angles to each other. In addition, an effort was made to measure every visible fracture in a collection of pebbles; in this way, more deformed pebbles were not assigned undue statistical significance. Clearly, the method is not entirely precise; accurate estimation of the trends of individual fractures was not always possible.

particularly where fractures terminate within the interior of a pebble. Additionally, the treatment of fractures aligned sub-parallel to the trend of roadcuts is a problematic one. In some cases, the planes could be correlated with visible contact marks and measured as usual. In other instances, they appear to be products of shattering associated with the construction of the roads themselves.

Despite these difficulties, orientation measurements are probably fairly accurate (i.e. $\pm 5^\circ$ for both strike and dip). At least 90 measurements were made at a given outcrop, and it is therefore considered that the results can be treated with a fair degree of confidence.

3.22 Results

Figures 3.1A-D present equal-area lower hemisphere projections of poles to fracture planes for data from Ablana, Aguilar, Olloniego, and Frieres respectively. Three important points are noted:

1. All plots show a definite preferred orientation, with a point maximum of at least 8 times a uniform distribution.
2. Three of the four plots (Aguilar, Olloniego, and Frieres) show some indication of a submaxima forming at high angles to the dominant maximum.
3. The orientation of the maxima are significantly different along the strike of the conglomerate unit. The measurements from Ablana and Aguilar yield a common pole cluster at 270/60, presumably because the localities are less than 2km apart. The trends at both Olloniego and Frieres, however, are significantly different; at Olloniego, a diffuse maximum is developed, spread widely from 090/40 to 200/60, with a maximum of 12 times uniform at 115/40. At Frieres, a tight cluster forms at 000/60, with a less strong grouping at 080/50.

FIGURE 3.1. Equal-area stereographic projections of poles to fracture planes, as measured in the field. Contours are drawn in terms of "x" times a uniform distribution.

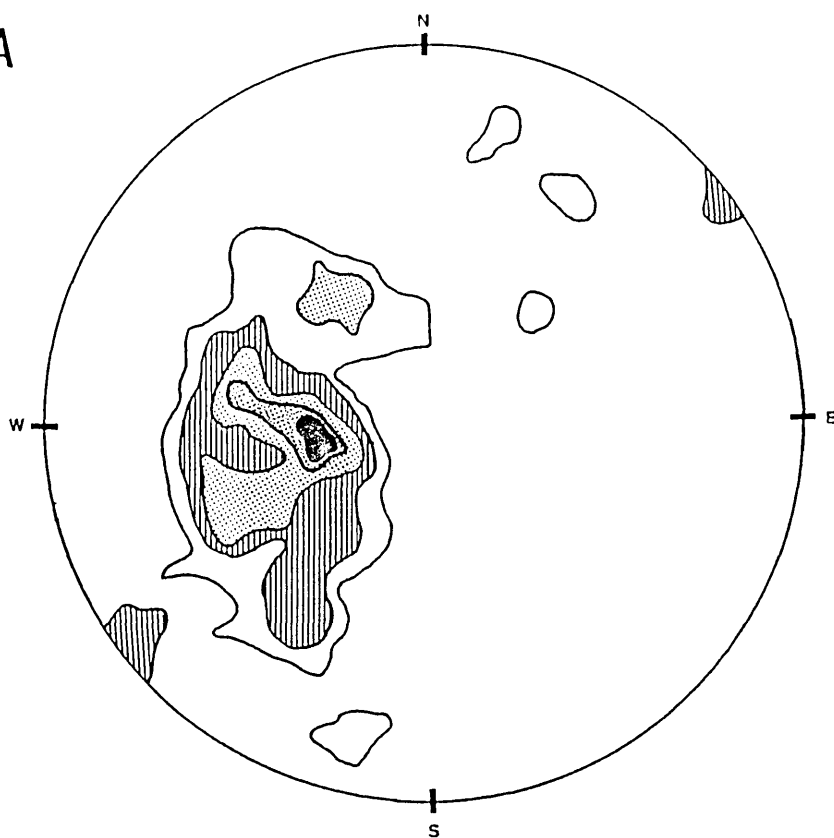
A) Ablana. 120 fractures; contours at 2,4,6,8,10 times uniform.

B) Aguilar. 90 fractures; contours at 2,4,6,8,10 times uniform.

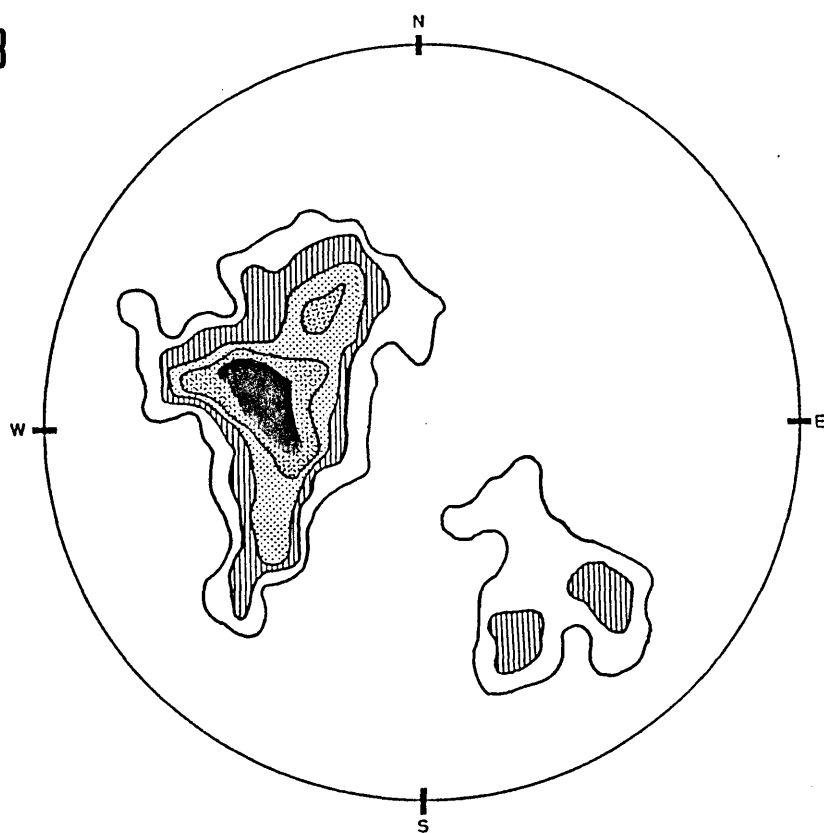
C) Olloniego. 166 fractures; contours at 1,3,5,7,9 times uniform.

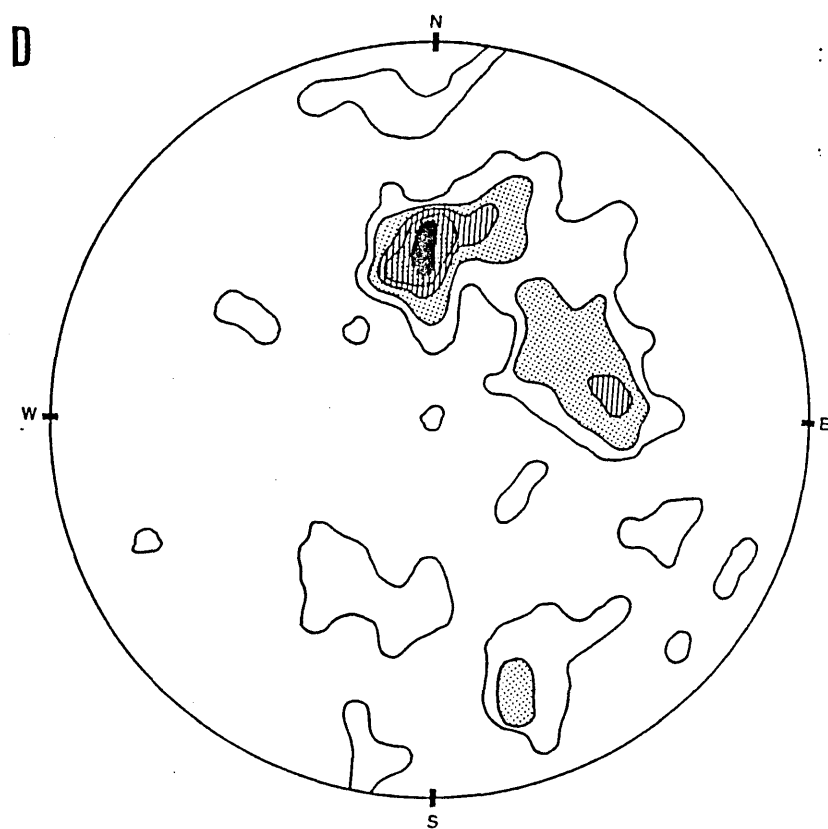
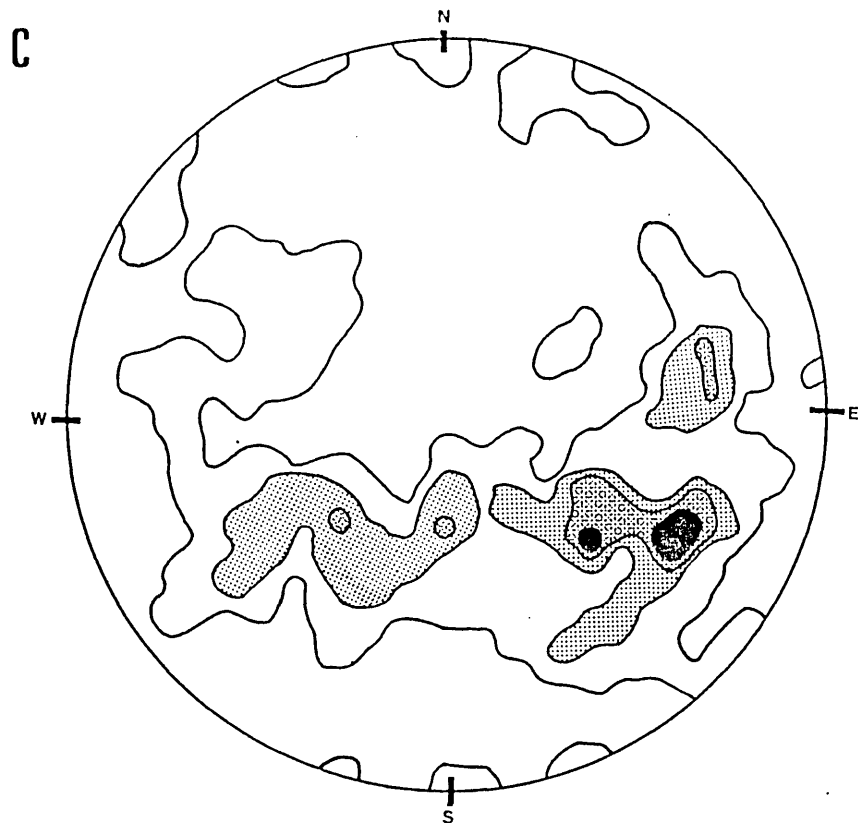
D) Frieres. 103 fractures; contours at 2,4,6,8,10 times uniform.

A



B





3.2.3 Discussion

The fact that a definite point maximum exists for each locality indicates that fracturing occurred in response to a non-hydrostatic stress field. Despite the fact that fractures initiate from point contacts whose normals are randomly oriented in space, some contact configurations initiate more fractures than others. Points (2) and (3) are much more puzzling. The fact that definite submaxima develop, however, would seem to indicate that not all fractures can be simple mode I extension fractures. In addition, the non-uniformity of fracture orientations must either indicate a very non-uniform stress field within the basin fill sediments at the time of fracturing, or reflect later rotation of beds without significant rotation between pebbles. Before proceeding with a discussion of the significance of the three points outlined above, it is instructive to consider the distribution of fracture orientations one would expect by assuming that actual fracture patterns correspond closely with the theoretical predictions discussed in the previous chapter.

Pure Extension Mode

If all fractures were purely mode I extension type, a single point maximum would be expected to develop in the plot of fracture poles. Fabric intensity would fall off fairly uniformly from that maximum, for two primary reasons. Firstly, contact points other than those whose normals are aligned parallel to the compression direction will radiate fractures, and pebbles might be expected to rotate in response to the applied stress. In addition, the shape of a given contact will influence the nature of the resultant fracture (recall Fig. 2.10), causing a variation in the angular spread. The method used to make individual measurements will tend to minimize that spread since in most cases the mean trend of a given set is taken to represent its orientation.

Combined Fracture/Microfault Mode

Not all rocks fail via mode I extension fracturing, particularly as the number of structural flaws in single loaded particles increases. Gallagher et.al.'s (1974) extension fracture criterion may indeed hold for individual grains (where the ratio of stress concentration near contacts to grain size is high), but for larger particles, the transition from extensional fracturing to failure along shear faults cannot be ignored. Results of rock deformation experiments on triaxially loaded cylinders indicate that at low confining pressures unhindered propagation of extensional cracks quickly leads to failure by axial splitting (e.g. Heard, 1960; Wawersik and Brace, 1971), a condition that could be described as "mesoscopic" mode I failure. Numerous studies (Nemat Nasser and Horii, 1985; Friedman and Logan, 1973), however, show that as the effective confining pressure increases, mesoscopic failure occurs along faults oriented at angles of 30° to 45° to the compression direction. The exact mechanism of failure is still widely debated (see Brady, 1974; Rudnicki and Rice, 1975; Cleary and Rudnicki, 1976; Peng and Johnson, 1972) but it certainly involves the formation of a critical density of extensional microcracks which coalesce and allow the rotation of particles along discrete fault surfaces. Detailed microstructural results of this study will be presented in the next chapter, but for the purpose of the present discussion, it is noted that both extensional fractures and shear faults exist in individual specimens, and the two cannot be readily distinguished on the basis of field evidence. In many cases, fractures which appear to have initiated in extension mode show evidence of later reactivation as shear surfaces, presumably as a result of local pebble rotations resulting from compaction. The predicted orientation of fracture poles will not be markedly different; extension fracture distribution will roughly mimic that produced by failure in extension mode. Depending on the ratio of shear faults to extension fractures, a definite submaximum (or pair of submaxima) will form at an angle of 30° to 45° degrees to the densest point maximum, but in practical situations, this may not be statistically

separable due to normal data scatter. Figure 3.2A illustrates two pebbles subjected to an applied load, figure 3.2B depicts two potential responses to that loading, and figure 3.2C shows the corresponding plots of fracture poles which might be expected to result from several pebbles undergoing similar deformation.

During the collection of orientation data in the field, no attempt was made to distinguish between the two classes of failure surfaces; it was tacitly assumed that fractures would develop only as mode I type. In some cases, a systematic topographic offset within sets of subparallel traces was observed (plate 3.1B), a feature initially attributed to preferential weathering due to enhanced fluid access. In retrospect, however, it appears that those offsets are a result of minor displacements of a millimeter or less on fractures with a consistent sense of shear (figure 3.3). Development of these step-like features is limited, however, to a small percentage of all fractured pebbles; of the 15 samples collected for microstructural study, only 2 show evidence of displacements large enough to enable reliable determination of the movement sense. By distinguishing between pebbles which show clear topographic offsets and those which do not, it might be possible to determine if a given maximum on the plot of fracture poles represents shear or extensional fracture trends, though the distinction might be blurred by the effects of shearing on initial extensional planes. At any rate, no such distinction is possible in the data from this study, since time constraints allowed for only a single field visit.

Despite these limitations, certain definite conclusions can be drawn from the three main features I have outlined with respect to the fracture pole orientation diagrams. The orientation of the point maxima at each locality seems to preclude the interpretation that deformation of the pebbles resulted purely from overburden stresses, a conclusion reached by Wiltschko and Sutton (1982) for the Pass Peak conglomerate on the basis of purely mechanical considerations. The magnitude of overburden might certainly have been sufficient to initiate fracture, but the

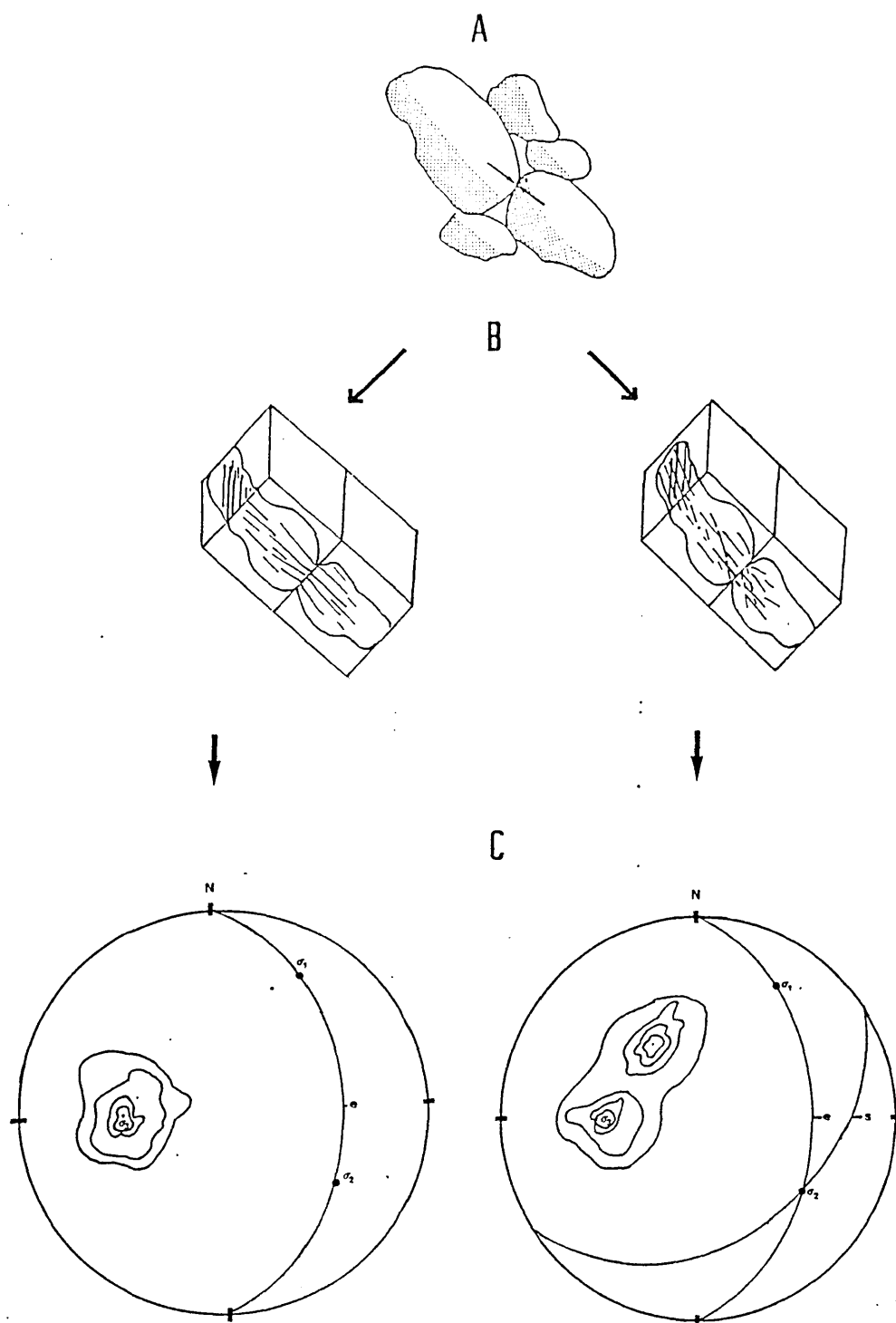


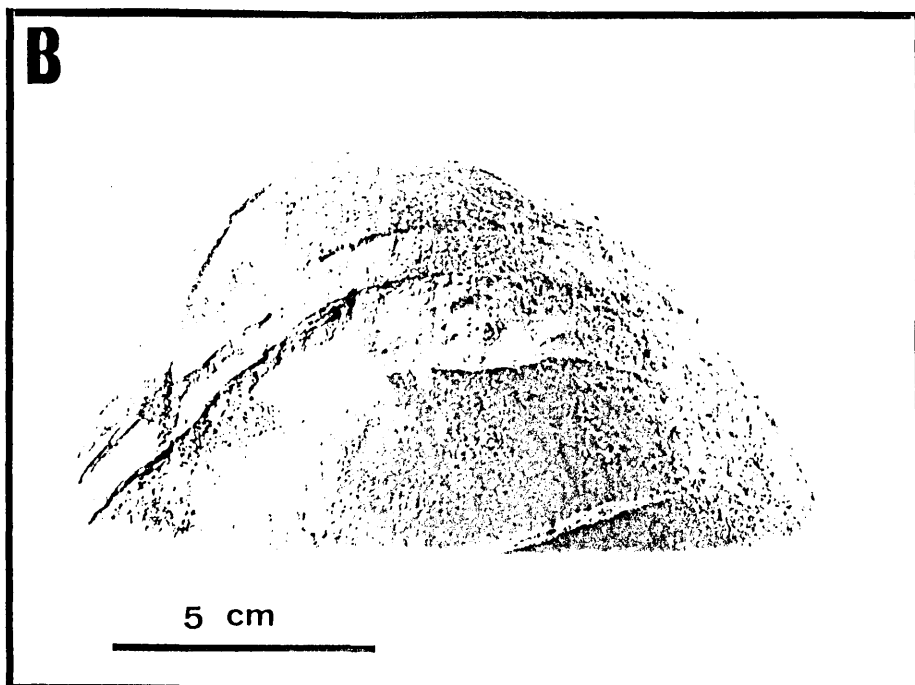
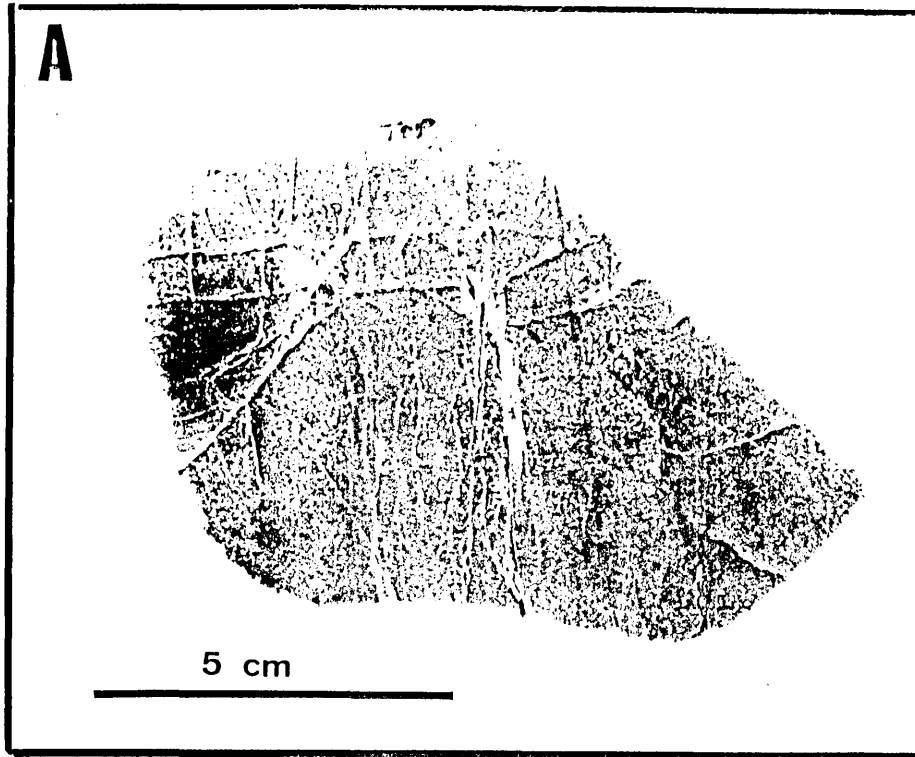
FIGURE 3.2. Schematic sketch illustrating potential response of a group of pebbles to a distantly applied load transmitted across impingement contacts. Diametrically loaded pair of pebbles (A) might fail via mode I extension fracturing (B i), or a combination of extension fracturing and shear faulting (B ii). (C) shows the equal-area projections which might result from field measurements at the outcrop.

PLATE 3.1.

A. Photograph of planar cut through hand specimen (OL2). Crack traces are visible, and these were used to prepare crack maps from a series of hand specimens (Figs. 3.9-3.17).

B. Surface view of hand specimen (ol3), showing the appearance of topographic offsets which result from small displacements along shear faults, as shown in Fig. 3.3.

PLATE 3.1



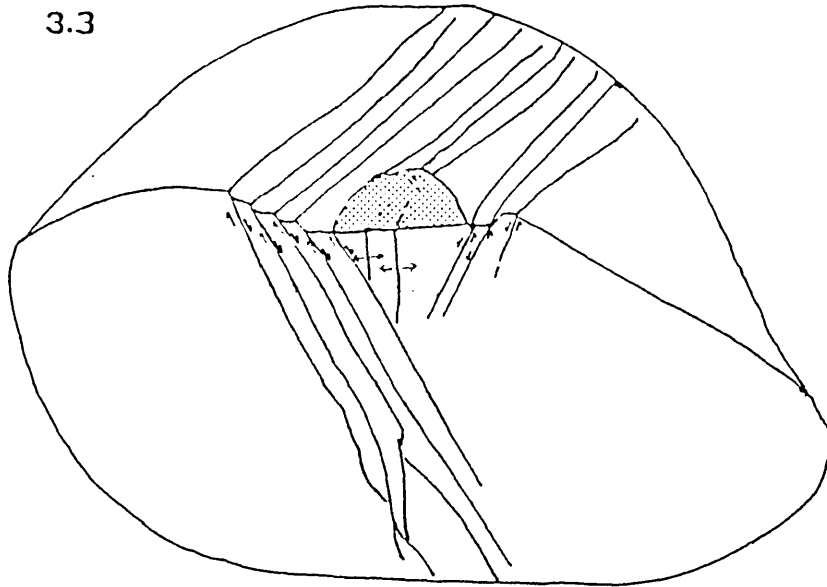


FIGURE 3.3. Sketch illustrating topographic offsets on pebble surface, produced by systematic offsets on microfaults with a consistent sense of shear.

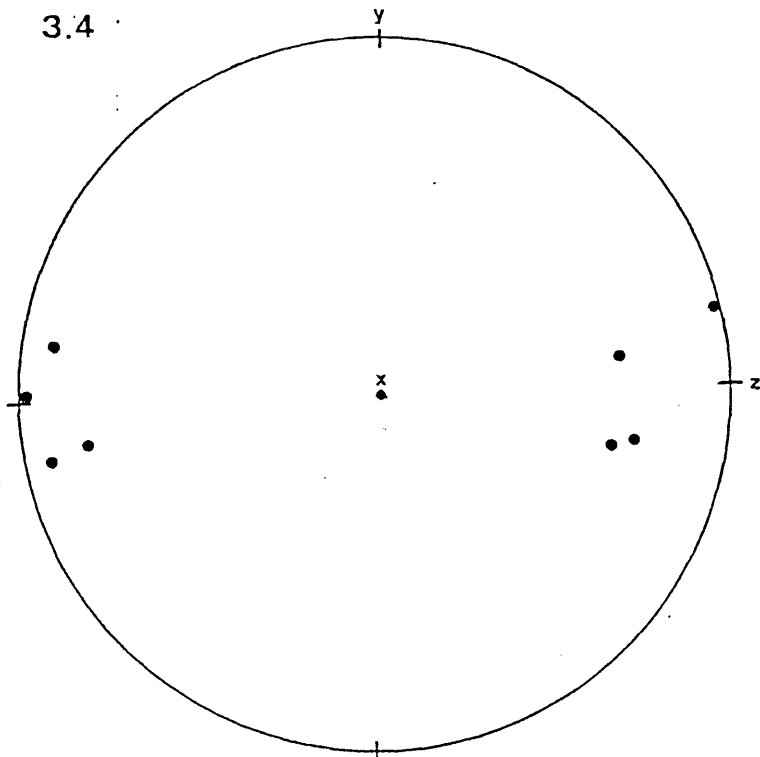


FIGURE 3.4. Orientation of faults produced in laboratory tests on cubic (22 x 22 x 22mm) samples of Sierra granite, as reported by Aydin and Reches (1982). Points represent poles to fracture planes, which appear to occur in 4 distinct groupings in an orthorhombic symmetry.

predicted orientation of the maximum principal stress associated with overburden would be near vertical. Regardless of the nature of the Mieres fractures, their dips should exhibit a tendency to cluster within 30 degrees of vertical. Instead, the maxima all correspond to fractures which dip at between 30° and 50° degrees, indicative of a non-vertical maximum compressive stress.

The position of submaxima in relation to the definite maximum at each locality seems to belie a consistent interpretation. The distribution of poles at Olloniego (fig. 3.1C) suggests a partial great circle girdle, or more exactly, two partial girdles which intersect at the maximum. The girdles might well represent loci of shear fault planes which have developed as a conjugate pair bisected by mode I extension fractures. The angular spread, however, seems too large (50° to 60° degrees along a great circle trace between pole maxima) to prove that interpretation. It should be emphasized, however, that both of the collected samples which show well developed shear planes come from Olloniego. Distributions from Ablana (fig. 3.1A) and Aguilar (fig. 3.1B) fit a combined extension fracture/shear fault model somewhat better. Both show well developed point maxima, with a corresponding spread of data confined to 35° - 40° degrees, along a great circle trace on either side of that maximum. The data from Frieres (fig. 3.1D) shows a slightly greater spread of poles (45° from the point maximum), but the additional variation falls within the range of possible measurement error outlined in section 3.2.1.

It should be noted that both the Aguilar (fig. 3.1B) and Ablana (fig. 3.1B) plots show statistically significant submaxima of poles in the southeast quadrant of the projection. In both cases, that submaximum occurs at least 90° along a great circle trace from the maximum, and cannot be fit to the models already described. Two possible explanations are proposed as alternatives.

- (1) Aydin and Reches (1982) proposed, after studying the orientation of several hundred faults in sandstones from the Western U.S., that faults

commonly occur in 4 distinct sets in a given area, in essentially orthorhombic symmetry. They report the results of a series of triaxial compression tests on rectangular shaped blocks, which confirm that similar distributions are seen in the laboratory specimens (fig. 3.4). If similar fault mechanisms were operative in the deforming pebbles, the right angled distributions seen might be products of the same single failure event; the measurement technique used in this study would almost certainly make the separation of 4 fault sets statistically impossible.

(2) The submaxima may represent a genetically different set of fractures, related to a shifted regional stress field. In Chapter 2, I noted that a second phase of deformation produced tightening of the Hercynian arc, and was responsible for a set of concentric folds which post-dated most thrust movement. If one assumes that the densest group of fractures formed during the development of the basic fold-and-thrust architecture, then the submaxima could be indicative of later tightening.

I have already discussed the difficulty of estimating principal stress directions to more than 30° degrees accuracy using the fracture pole maxima as input data. Nonetheless, a range of stress orientations can be postulated for each locality on the basis of those pole distributions. If one assumes that the direction of maximum principal stress is oriented at 90° to both the line of intersection of the possible shear fault and extension fracture planes, as well as the inferred direction, then a partial great circle can be drawn to represent the range of possible compression directions (fig.3.5). There appears to be sufficient lack of overlap of these calculated ranges to justify the conclusion that stress is heterogeneous along strike of the conglomerate unit. Bedding strikes vary by less than 20° and dips by less than 15° degrees between the

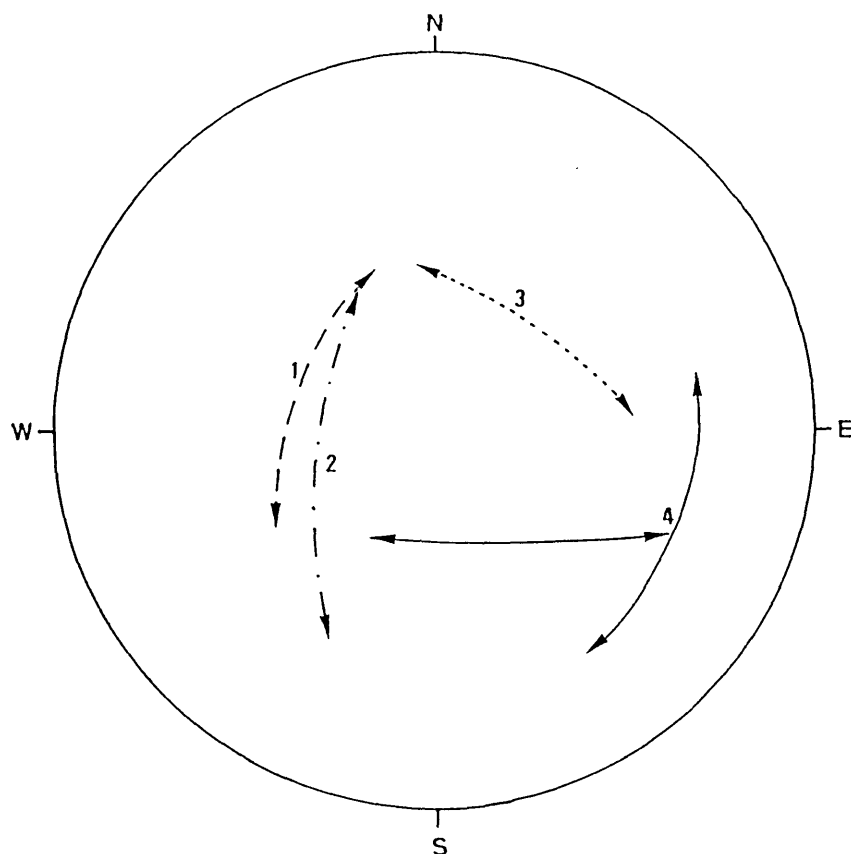


Figure 3.5. range of compression directions inferred from field data at the four localities of fig. 3.1. (1) Ablana, (2) Aguilar, (3) Olloniego, (4) Frieres. Position of maximum compressive stress is assumed to be perpendicular to the line of intersection between extension fractures and shear faults, as well as the inferred σ_3 direction.

four localities studied, which implies that the scattered distribution of compression directions is not a result of rotation of the entire conglomerate unit during arc tightening. Instead, it must be a result of changing thrust geometry in the zone near the western limit of the Central Coal Basin. Work by Rowe (pers.comm. 1985) using calcite twin lamellae as paleostress indicators should test the preliminary conclusions reached on the basis of this fracture study.

3.3 2-DIMENSIONAL DATA

Pebbles were collected from three localities for the purpose of studying the characteristics of individual fractures in greater detail. While the results of this part of the study help to clarify the conclusions reached in the previous section, the general aim of the 2-dimensional analysis is to characterize the crack patterns observed, and to explore the effect of scale-dependence on the degree of preferred orientation evidenced in a given pebble. All work was done with the aid of a hand-digitizing pad and microcomputer; programs developed in this prototype study should serve as the basis for further, systematic statistical analyses of the distributed crack behavior in cataclastically deformed rock.

3.3.1 Sample Preparation

Logistical constraints prevented me from collecting more than a few select pebbles from a given locality. As a result, the small sample size dictated the way in which sections were cut and prepared for study. Most specimens were cut roughly parallel to the long axis of the pebble, in a plane which contained the greatest number of visible fractures. For statistical purposes, two mutually perpendicular planes cut in the same orientation for all pebbles would have enabled a more complete comparison with the three-dimensional work outlined in the previous section. The method chosen, however, ensures that the area of a given

fracture network most likely to show microstructural evidence for phenomena associated with failure can be studied.

Three distinct sets of data have been analysed quantitatively, with the aim of exploring the variety of information one can obtain at different scales of observation. (1) Overall crack pattern networks were studied directly from the faces of rocks cut for thin section preparation. Plate 3.1A shows the appearance of the cut face of specimen OL2; a relatively dense fracture network is visible to the naked eye, and resolution is enhanced by smearing several droplets of immersion oil onto the rock face. Hand tracings of all observable cracks were made at true scale, and the subsequent maps were enlarged to magnifications of between 2x and 4x for digitizing. (2) Large (3"x2" or 3"x4") thin sections were prepared for several pebbles, and studied using standard optical techniques. Transmitted light photomosaics of two of the sections were prepared. Visible cracks were traced onto successive A4 (297 x 210mm) sheets, and subsequently digitized. Raw data was filtered using Program WFRCOR (see Appendix 1 for program descriptions and listings), which assembles individual sheets into a global map. (3) 6 1"x2" thin sections were prepared, mechanically polished, and studied with reflected light, transmitted light, and SEM techniques. Crack statistics were obtained from reflected light photomosaics of each slide, using the technique described above. Several authors (Brace et.al., 1972; Simmons and Richter, 1976) have questioned the use of mechanical polishing on cracked samples. While evidence from this study supports their claims that the process generated a limited number of new microcracks, it seems less likely that cracks of the size measured here (most transect or follow the boundaries of several grains) are produced during the preparation process. Ion milling of specimens which contain stress-induced microcracks appears to be the favored polishing technique (Kranz, 1984), but Hadizadeh and Rutter (pers.comm.) noted that, when used on sands cemented by optically continuous silica overgrowths, the etching process accentuates all grain boundaries, rendering a distinction between cracked

and uncracked boundaries impossible. In general, the results obtained with a fine mechanical polish appear to be acceptable. Crack densities are reported in terms of percent of total plotted against orientation. Where assessments of absolute densities are made, it is done in qualitative terms, in order to characterize the relative damage within a set of pebbles. If the preparation process does indeed generate new cracks, the number generated should be similar for all thin sections.

3.3.2 PETROSTRUCTURE ANALYSIS

3.3.2.1 Introduction

Attention within the rock deformation literature is generally moving toward attempts to relate a number of bulk rock properties (e.g. permeability, resistivity, and a range of elastic deformation and failure properties) to the overall structure of a given rock type. Warren (1982) defines the general term petrostructure to denote the combination of mineralogical, petrographic, and microstructural variables which characterize the bulk physical properties of a rock. In that study, he outlines a statistical approach to the problem of correlating bulk properties to the corresponding petrostructure, and demonstrates the method with a prototypal study of two granites from a U.S. Department of Energy borehole in New Hampshire. The same general approach is used in this study, but significant simplifications have been made to the statistical programs to make them more directly applicable to the microstructurally simpler quartzite starting material. On all scales, I have been chiefly interested in assessing the degree of visible damage, as represented by cracks and microcracks resolvable on the basis of visible contrast and morphology, using the microscope facilities available at Imperial College. Blenkinsop and Rutter (1985) discuss the use of cathodoluminescence in studying cataclastically deformed natural rocks, and conclude that C.L. techniques can often delineate microcrack margins as lines of non-luminescing quartz, which otherwise appear as

trails of bubbles when viewed optically (Knipe and White, 1979). Because C.L. facilities are currently unavailable, it was concluded that statistical analyses at the magnifications used by Warren (1982) might reveal only a limited subset of the cracks which were actually important in controlling mechanical behavior. As a result, a wide range of nodal (i.e. unidimensional) parameters have been omitted from the petrostructure study, because they require an exact and detailed knowledge of all cracks in the section studied if they are to be of use.

Quite clearly, a more detailed study of bulk physical properties would require the identification of features such as distance between crack branches (i.e. crack diffusion distances), spatial distribution of crack forking zones, and interrelationships between crystallographic orientation and crack length and orientation data. At magnifications low enough to enable the study of longer, and often wider, cracks, however, overall crack behavior seems to be most strongly controlled by the principal stresses in a given pebble, which in turn depends upon that pebble's particular load configuration.

3.3.2.2 Model Data

Bearing the above considerations in mind, the statistical analysis in this study is based on purely linear data. The determination of both crack number and density with respect to orientation was deemed particularly important. In addition, the crack length distribution was computed for each sample analysed. Because of the exploratory nature of this work, several mapping techniques were tested, and these essentially form a continuum between two end-members. At one end of the spectrum, mapping was done with the aim of digitizing the minimum number of endpoints between line segments. Using this approach, kinks in a single long crack are ignored, and where cracks fork or branch, an attempt is made to incorporate one branched segment into a longer crack which proceeds in both directions from that branch point. Where dense networks of cracks coalesce to form a sub-parallel set, their trend is approximated by mapping one

or two representative cracks on the digitized grid. Only where the curvature of a single crack exceeds some large value (usually between 30° and 40° degrees) is the crack subdivided into branches for the purpose of revealing that curvature.

At the other extreme, the resolution of the digitizing pad itself is taken to be the controlling factor in determining how a crack pattern is mapped. The digitizing pad used in this study (a British Microcomputer Company GRAFPAD) contains 256 pixels in a vertical and 320 pixels in a horizontal direction. Because orientation data was segmented into 10° degree intervals, it was concluded that the orientation of cracks shorter than two GRAFPAD grids (16 pixels in both length and width) could not be accurately calculated. This is defined as the minimum resolvable length, henceforth referred to as MRL. In order to accurately resolve the orientation of a grain boundary for a sandstone with a 200um average grain size, micrographs with magnifications of at least 100x are thus required.

Cracks shorter than the MRL were either omitted or linked together to form one longer crack, if their angles were determined to correspond closely. All other features were mapped as accurately as possible. Where crack trends curved, enough points along the trend were digitized to keep deviations to within approximately 10° degrees. Kinked segments were mapped, provided the kink was longer than the MRL. Where closely spaced crack sets coalesced, the MRL was used to determine the spacing between sub-parallel cracks mapped to represent that set. Figure 3.6A depicts a typical crack network; in figure 3.6B the features which would be mapped using the "minimum number of endpoints" method is shown, while 3.6C shows a map produced on the basis of the alternative MRL criteria.

3.3.2.3 Analysis

Both methods of mapping have specific advantages. While the "minimum number of endpoints" method produces a considerably less faithful reproduction of the original network, it gives a truer value for crack lengths. It does

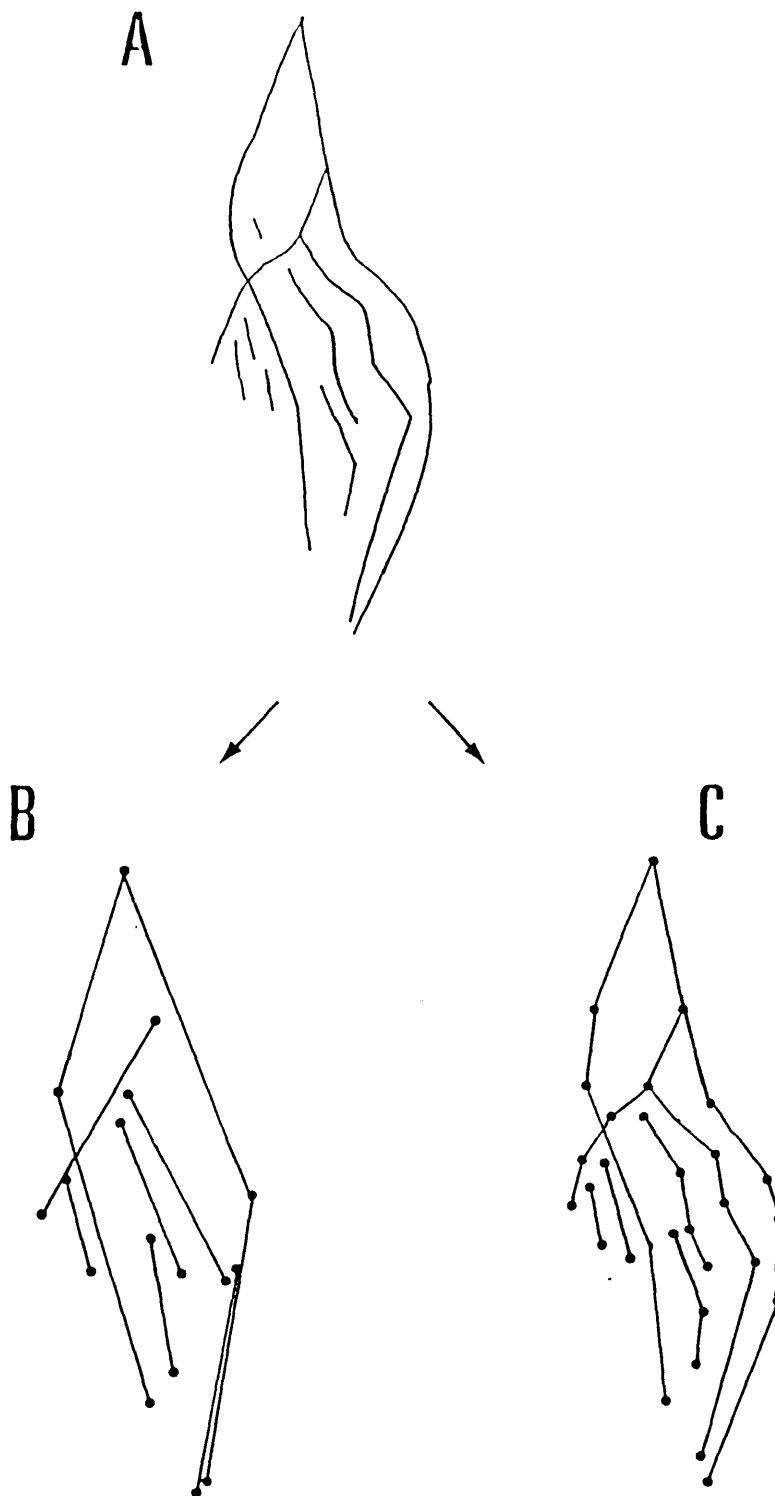


FIGURE 3.6. Comparison of two different hand-digitizing techniques used in this study. (A) shows a hypothetical network of crack traces. The appearance of a digitized map prepared using the "minimum number of endpoints" method is shown in (B), and the alternative "minimum resolvable length" (MRL) map in (C). For descriptions of the decision criteria, see section 3.3.2.2 of text.

ignore deviations in crack path, but nonetheless provides a reasonable approximation of the overall trend of the set. With the MRL method, the original network can be very nearly regenerated with appropriate plotting utilities. Crack length statistics, on the other hand, are rendered virtually meaningless. Instead of characterizing the true length of an individual crack, the distance between adjacent endpoints simply measures the tendency for that crack to deviate course during propagation. Where numerous interfering cracks are present, the mean computed length is further reduced, as the pattern transforms to a "patchwork" structure.

By incorporating nodal variables into the statistical program, the limitations of the MRL technique can be avoided. When an endpoint is digitized, it can be assigned a set of codes to characterize it as a branch point, a kink, or a crack tip. When processing data, the program can then link connected segments to generate additional variables, such as true crack lengths. The additional information for a given node enables the computation of a range of added statistics (e.g. nearest neighbor distances between crack tips, maximum and minimum branch angles), which render the data more amenable to a complete fracture mechanics analysis.

Because the incorporation of nodal variables requires a considerable amount of additional computer memory, I have rejected their use in this study. There is an inverse relationship between the number of cracks which can be stored in a fixed memory space (32 Kbytes in the BBC Model B micro), and the amount of information one can attach to a given crack. I have instead chosen a compromise, which afford a good measure of the orientation distribution of cracks, but accepts the fact that crack length measurements will not show a direct relationship to the degree of structural damage in a specimen. Briefly, the analysis routines take data generated using the MRL criteria, and calculates both the number and density of cracks in terms of orientation. Because all cracks of size greater than the MRL were mapped, the crack number statistics can give undue weight to the significance of smaller cracks. As a result, density vs. orientation is probably the most useful

statistical measure of preferred crack orientation in a sample. Crack densities have been computed as follows:

$$D = \Sigma(\text{length})^2/100$$

which is expressed in terms of percent of total cumulative density. Lengths have been squared to account for the fact that, while in a plane section cracks appear to be linear, they are actually planar features. The density parameter thus effectively weights longer cracks more heavily than short ones. If one assumes that the longest cracks are those which encountered the least resistance to propagation, and thus contribute most strongly to specimen failure, that weighting appears warranted.

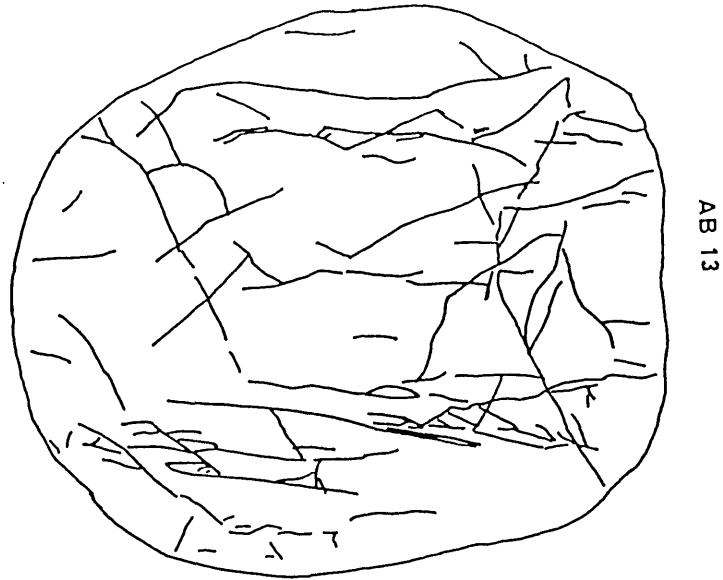
3.3.3 RESULTS

Orientation Analysis

As stated in the previous section, mapping based upon the MRL criterion affords a faithful reproduction of a given crack pattern. Figure 3.7A is a hand tracing of a slice through sample AB13, and Figure 3.7B shows the corresponding computer map. Because there is no fundamental difference between the two patterns, I have elected to present the computer maps in lieu of hand tracings. The positions of samples within the conglomerate unit are shown in figure 3.8. Figures 3.9 through 3.17 show the computed maps for the collective set of tracings; the outline of pebble edges are marked. Rose diagrams which present both crack number and crack density as a function of orientation are included. In each case, the horizontal diameter drawn through the half-circle contours is aligned with the horizontal (long) axis of the computer maps. Insets are provided with each figure, which show the stereographic projection of the plane of section, and the long (squares) and short (dots) map axes are indicated.

The technique used in digitizing cracks from thin sections is very similar to that used for hand tracings. Reflected light photomosaics were prepared, and resolvable

A



B

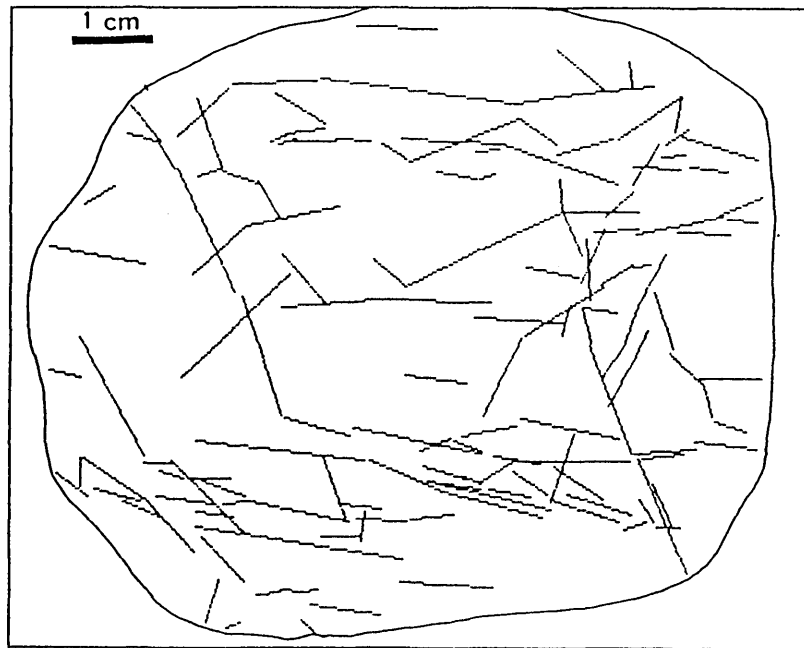


FIGURE 3.7. Comparison of computer generated crack map (B) with original hand tracing (A). From specimen AB13.

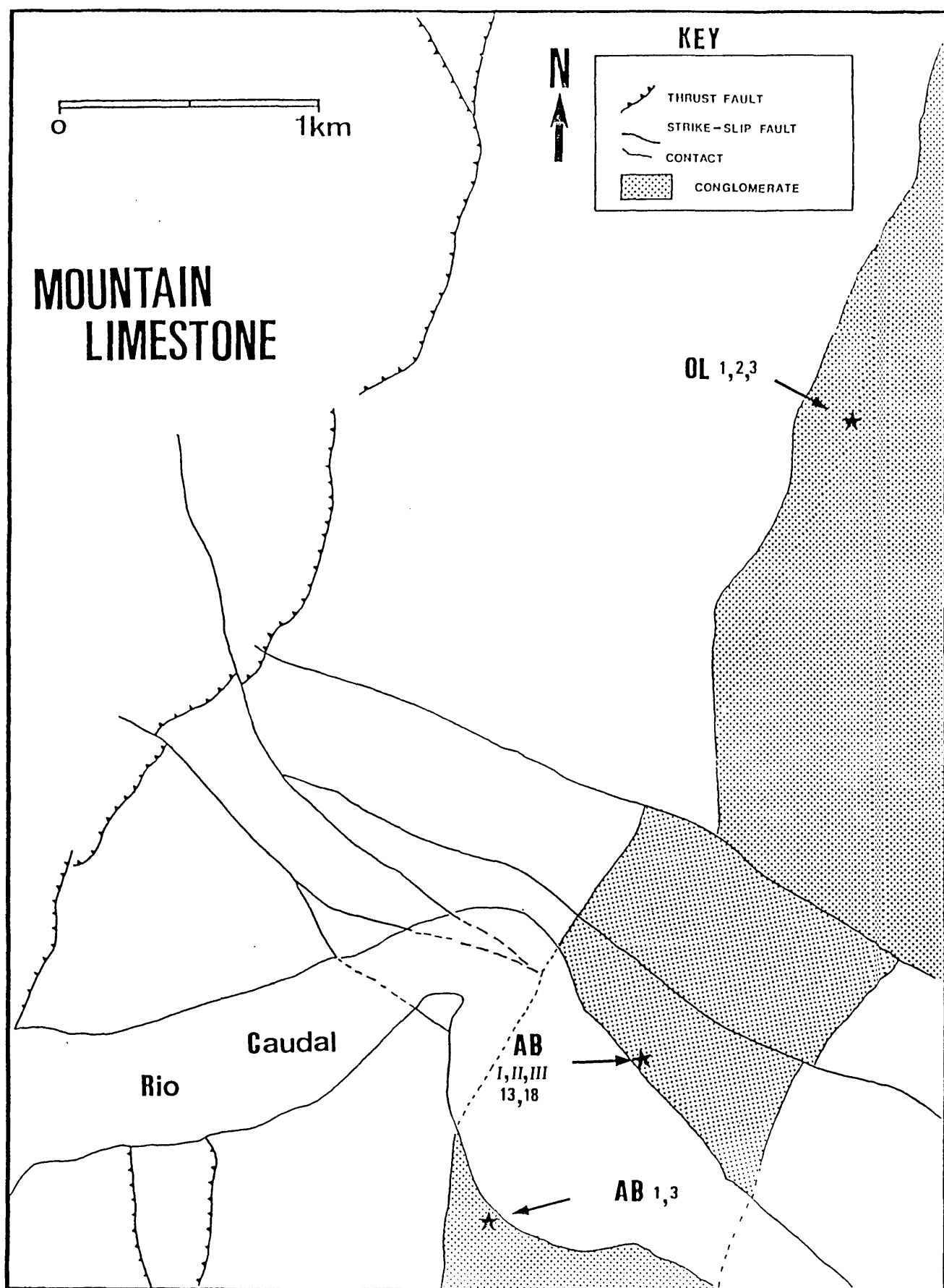


FIGURE 3.8. Locality map showing positions of specimens collected for microstructural study. (After Salvador (unpub)).

FIGURES 3.9 - 3.17. Results of 2-dimensional orientation analysis from hand-tracings off of cut rock faces. For each sample, Rose diagrams of crack number (top) and crack density (middle) vs. orientation are shown, along with the computer-generated crack maps (upon which pebble outlines have been superposed). The inset at the top right-hand corner of each figure represents the equal-area stereographic projection of the plane of section. The long (squares) and short (circles) map axes are indicated. These correspond to the horizontal and vertical axes of the Rose diagrams, respectively.

MAP# MCAB1
OF CRACKS= 286

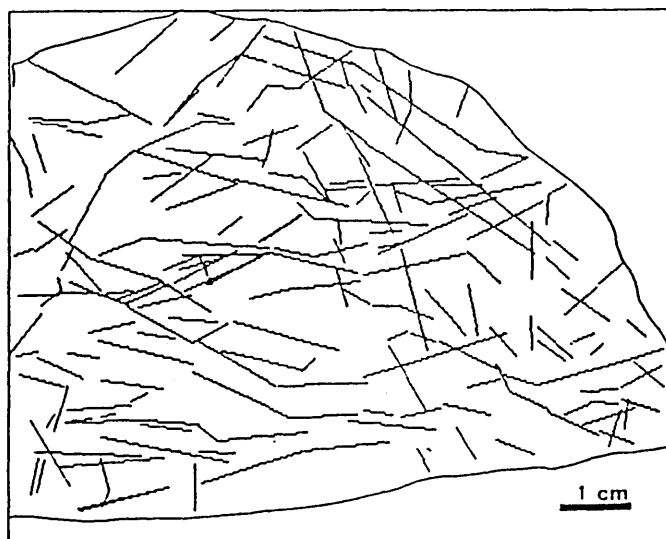
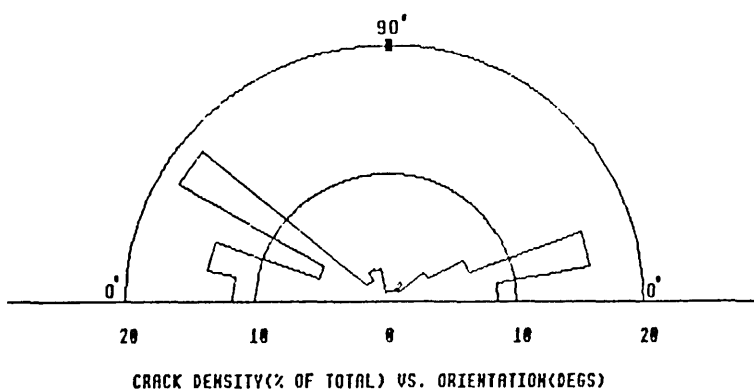
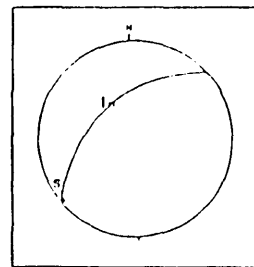
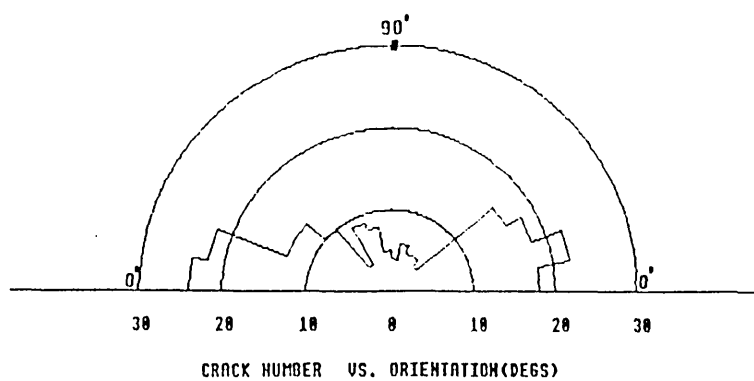


FIGURE 3.9. Orientation data for specimen AB1.

MPO M0003
OF CRACKS= 152

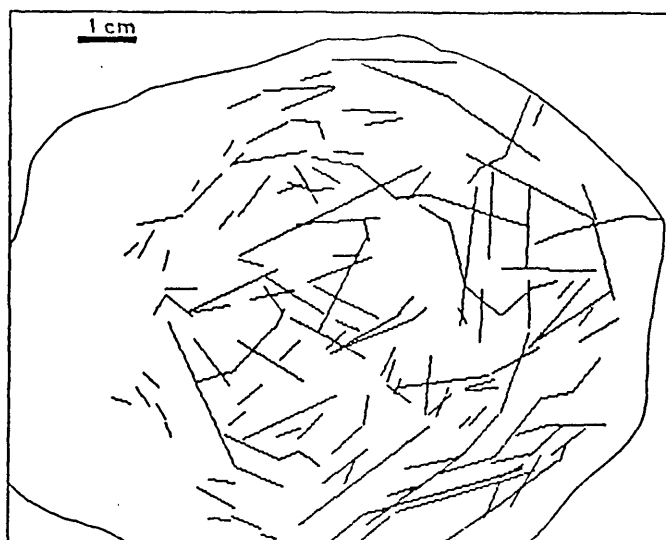
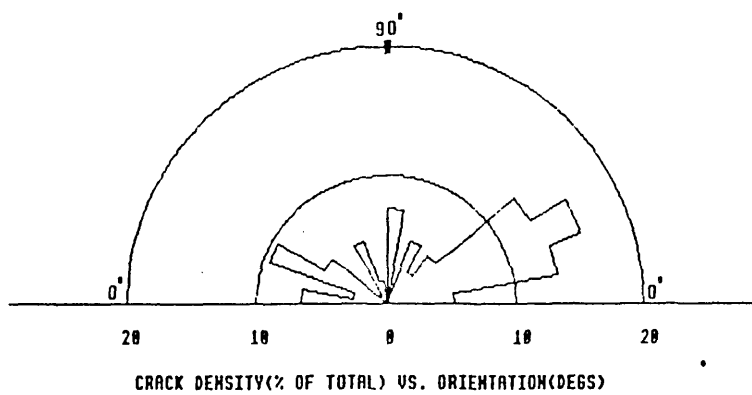
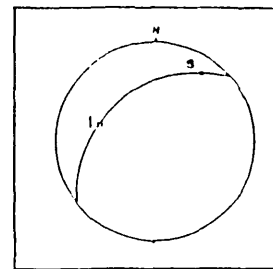
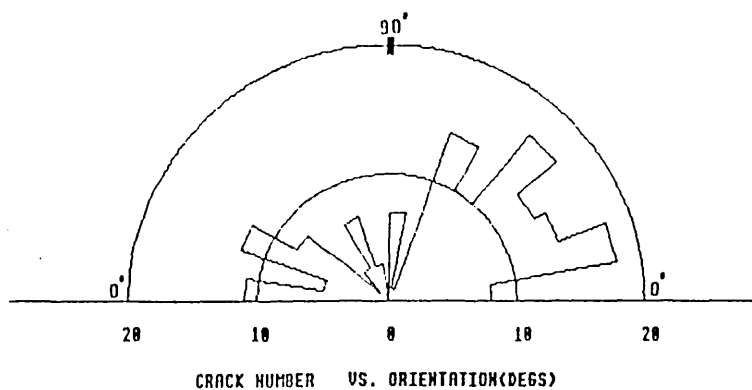


FIGURE 3.10. Orientation data for specimen AB3.

MAP# MCAB13
OF CRACKS= 146

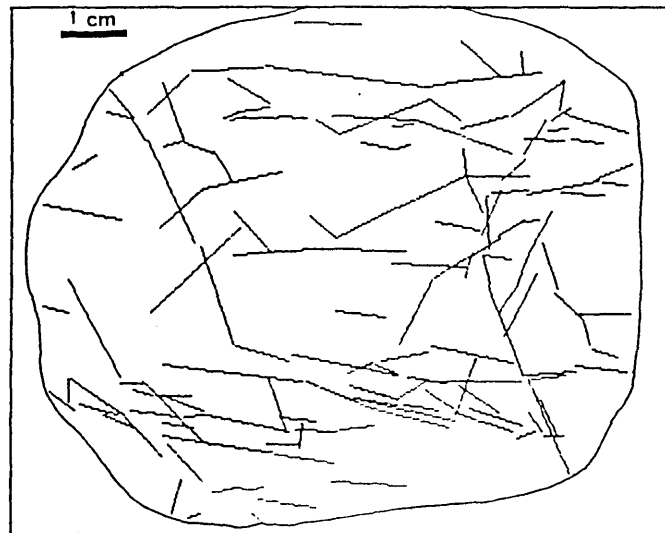
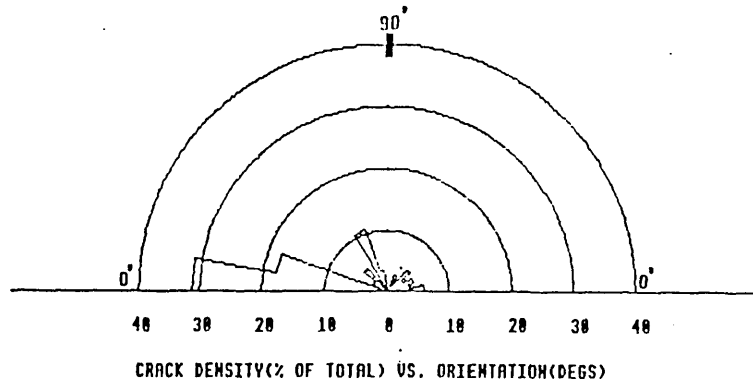
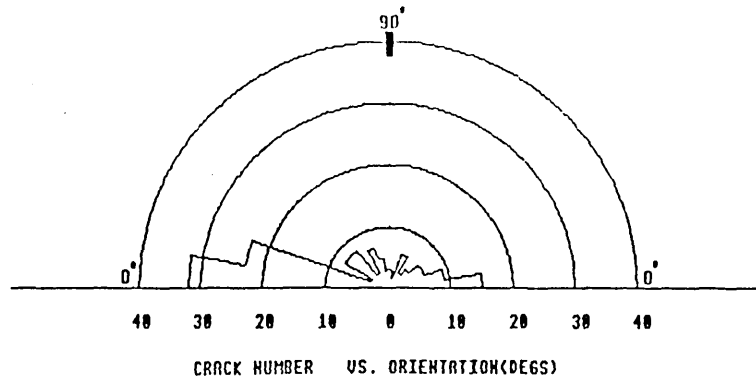


FIGURE 3.11. Orientation data for specimen AB13.

MAP# MCAB13B
OF CRACKS= 205

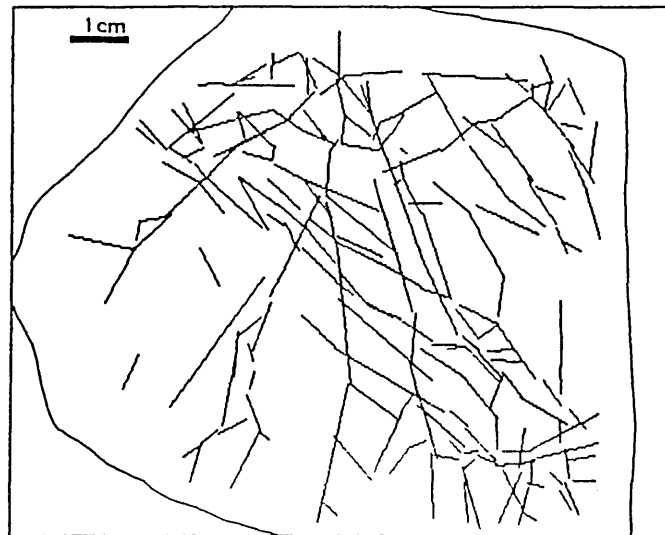
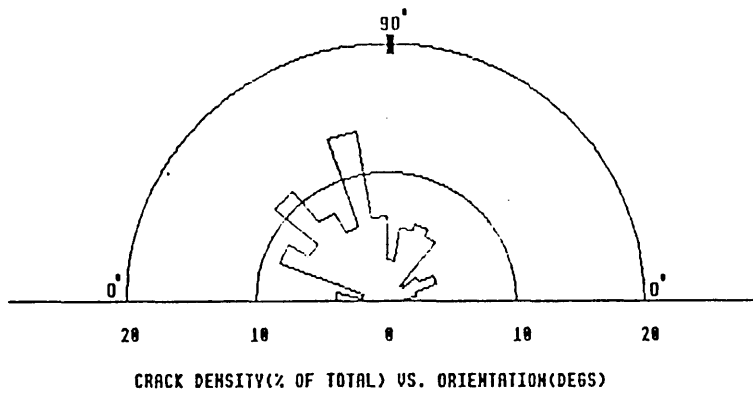
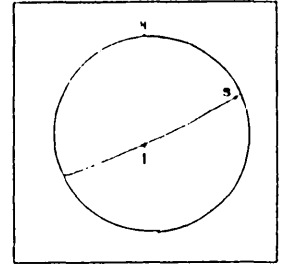
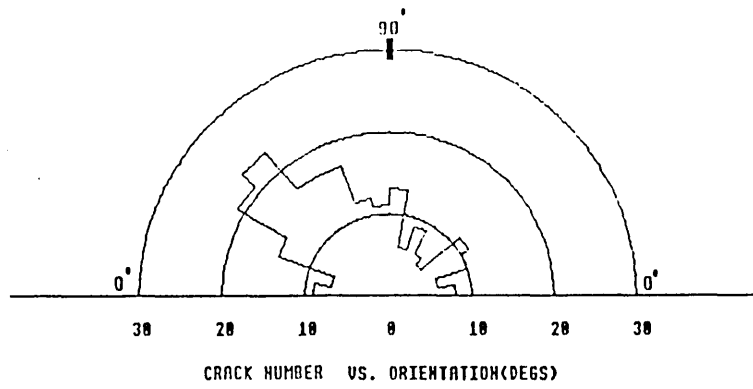


FIGURE 3.12. Orientation data for specimen AB13B.

MPD MICR018
OF CRACKS= 126

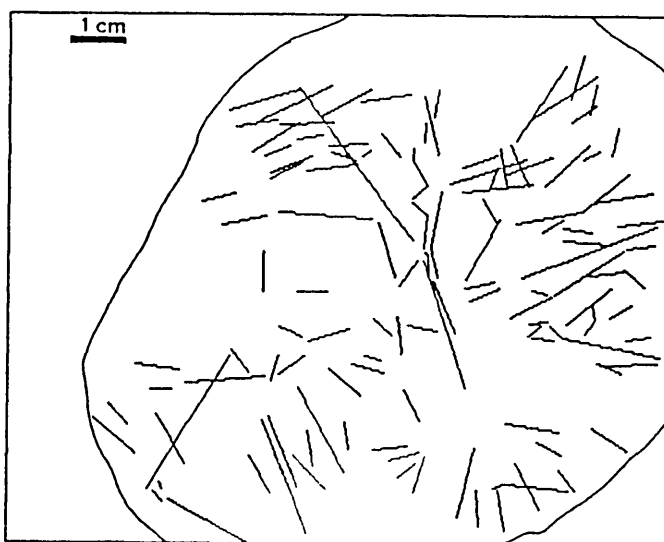
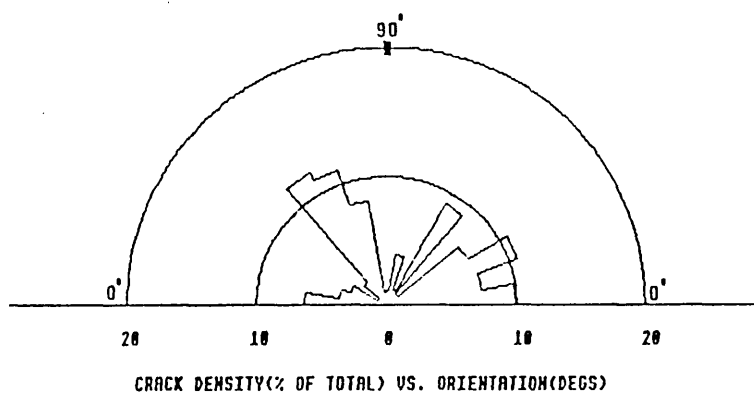
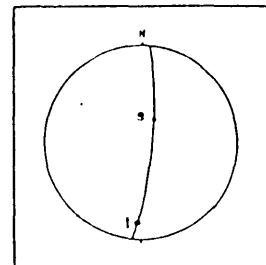
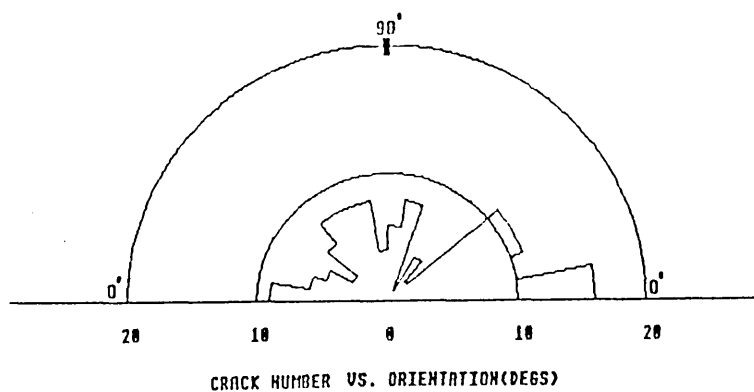


FIGURE 3.13. Orientation data for specimen AB18.

WIP MACOL 20
OF CRACKS = 92

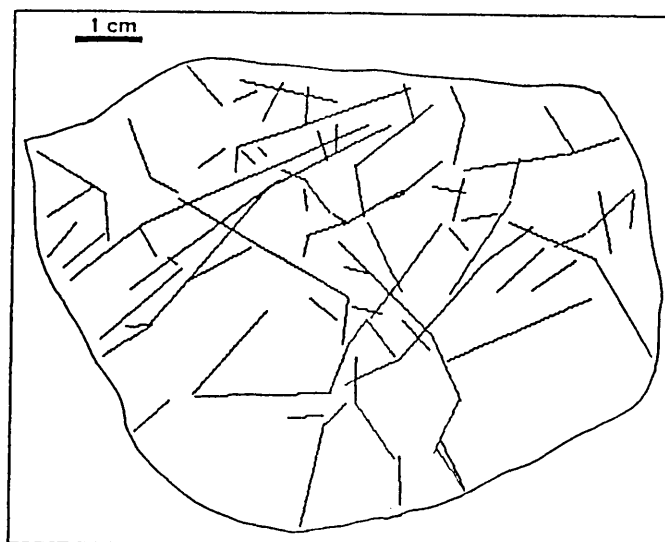
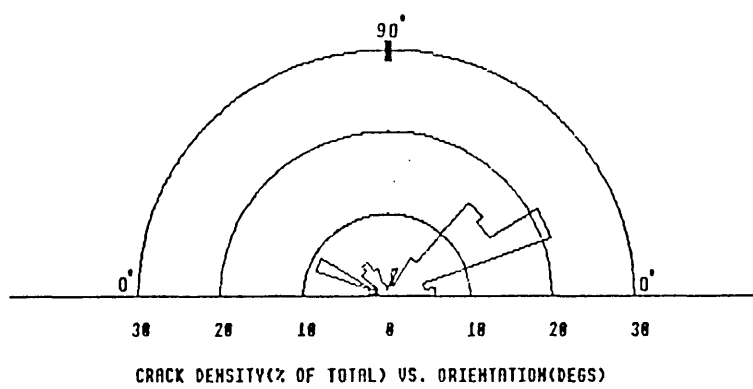
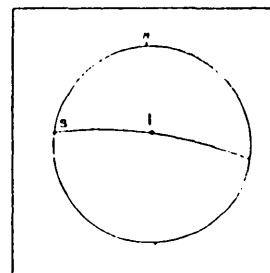
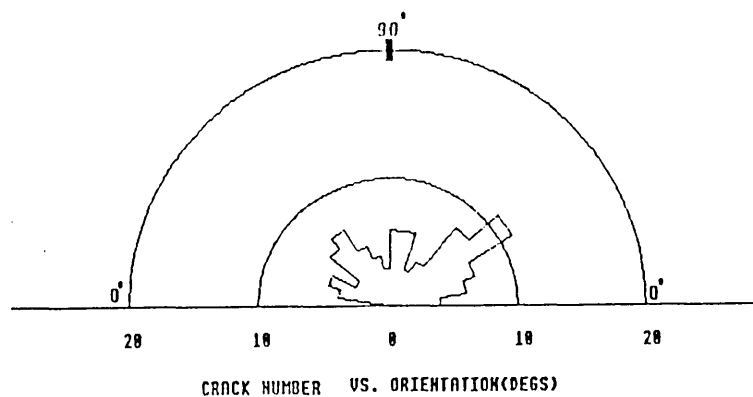


FIGURE 3.14. Orientation data for specimen OL2A.

MIP# MICOL2B
OF CRACKS= 55

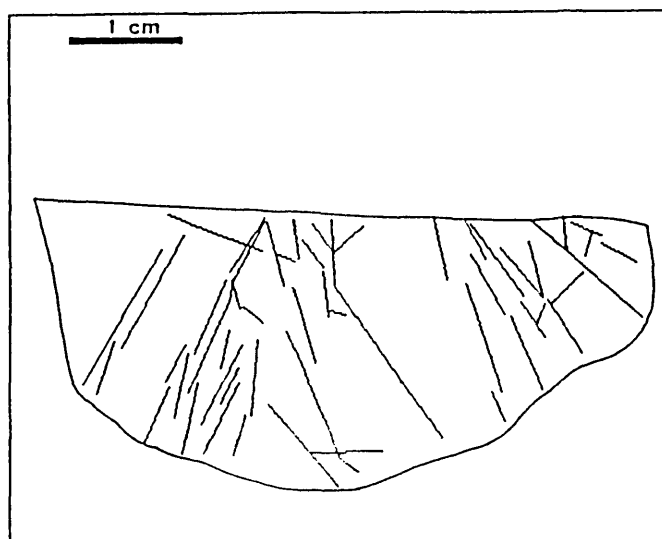
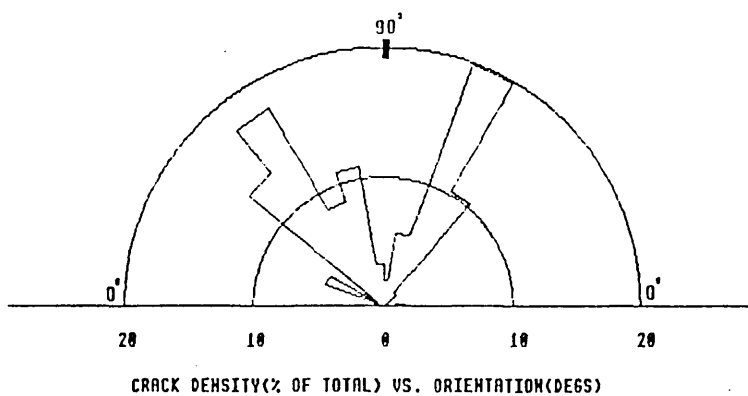
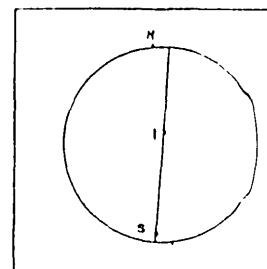
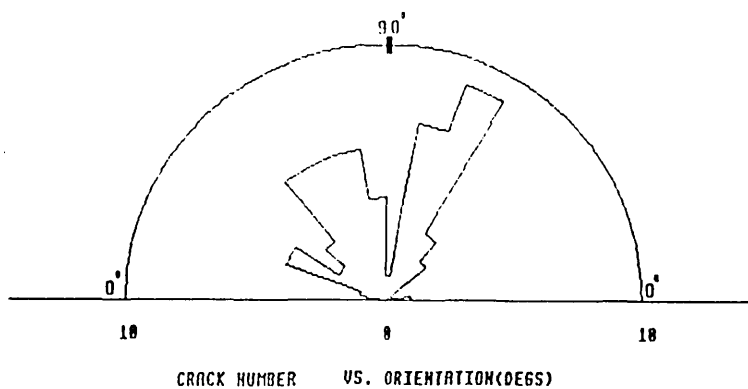


FIGURE 3.15. Orientation data for specimen OL2B.

MAPN MAC01.3
OF CRACKS= 155

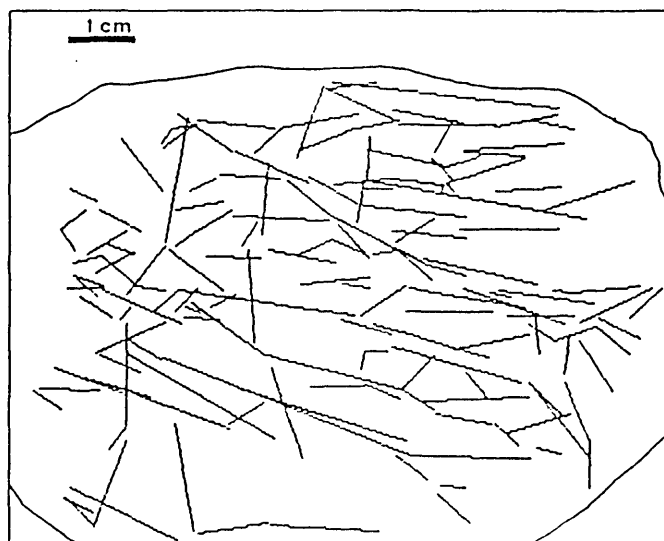
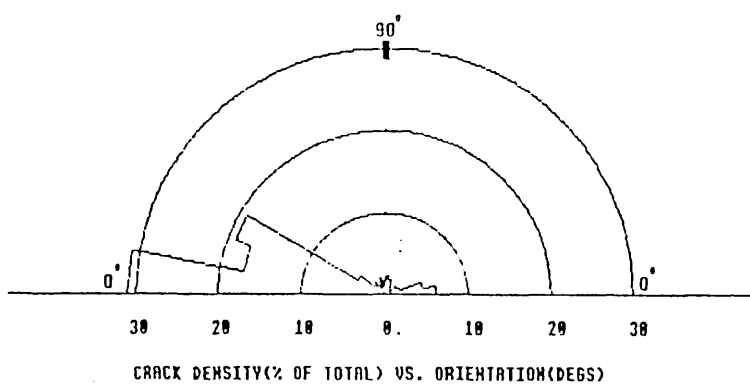
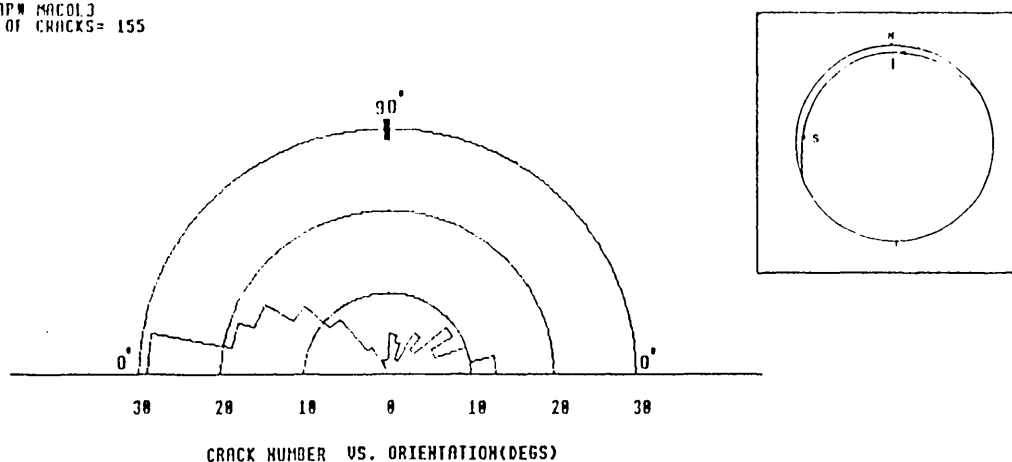


FIGURE 3.16. Orientation data for specimen 013.

MAP # MCOL3B
OF CRACKS= 87

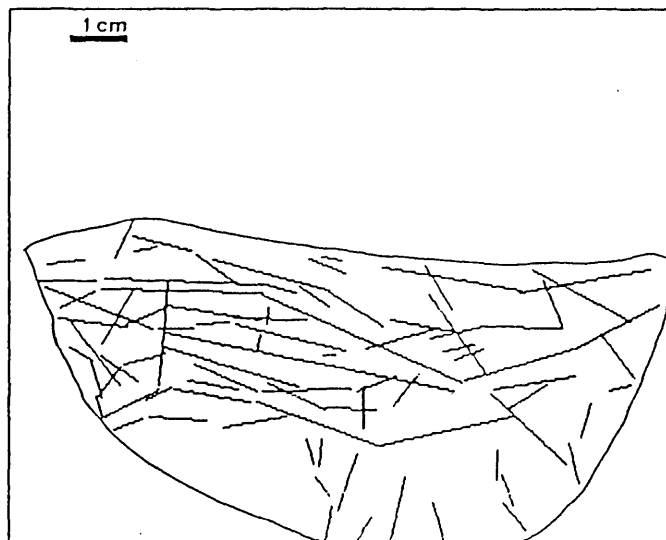
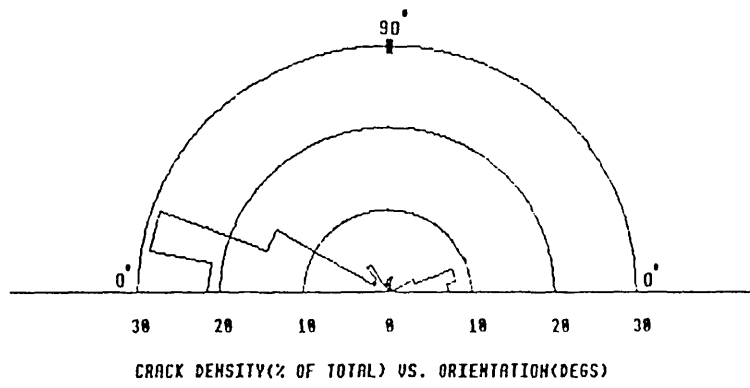
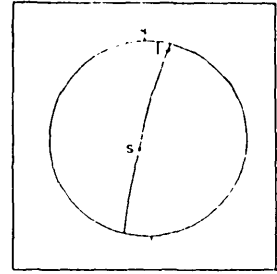
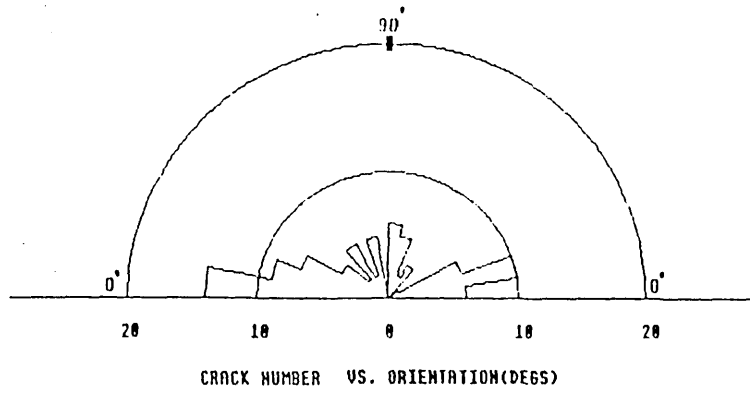


FIGURE 3.17. Orientation data for specimen OL3B.

cracks (again defined in terms of the MRI criteria) were traced onto large sheets of tracing paper and subsequently digitized as successive A4 sheets. With the aim of utilizing the highest resolution graphics mode available with the BBC microcomputer, the digitized coordinates were scaled to fill the entire screen, then printed in mosaic fashion using screen dump facilities (see Appendix 1). A total of five polished sections were analysed in this way; Plates 3.2 to 3.6 illustrate the results, and figures 3.18 - 3.22 show the corresponding Rose diagrams. The reflected light photomosaics are provided for the purpose of comparison with the computer-generated maps. The maps are very faithful to the original photographs, but it should be noted that in regions with the highest densities of fractures, it was necessary to make certain adjustments. Because most specimens were loaded to a point where throughgoing cracks transected entire pebbles, two distinct hierarchies of cracks are present. The magnification chosen (11x to 13x) for analysis enabled the mapping of complete thin sections, but was too low to resolve grain-scale microcracks. Where dense arrays of short cracks are separated by longer bounding cracks, a qualitative assessment of crack density in these zones was made, and a representative number of shorter cracks were subsequently digitized. For this reason, absolute densities are probably underestimated. Nonetheless, densities can be compared in a qualitative sense to determine the relative surface energy generated due to cracking in each specimen.

As a final example of the use of the quantitative petrostructure technique, I have included a mosaic map of 6 individual computer maps produced from a transmitted light photomosaic at 27x magnification. Plate 3.7 is a photomicrograph of part of specimen ABI, and figure 3.23 shows the corresponding map mosaic. While the results are similar to those obtained from the reflected light photomosaics, the example serves to illustrate the power of the digitized analysis when used to treat large maps. When used in conjunction with the program WFRCOR, features which transect several maps can be separated into individual files, then pieced together for statistical study. It is

PLATES 3.2-3.6 / FIGURES 3.18-3.22

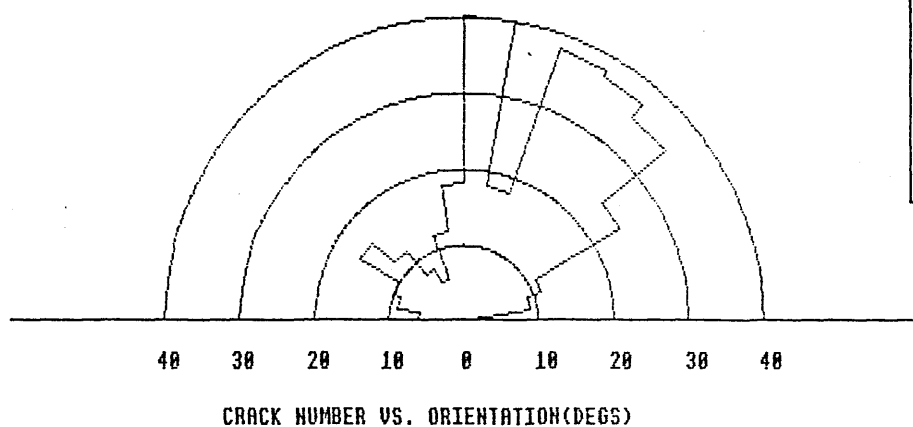
Photomicrograph mosaics and computer generated crack maps from polished thin sections viewed under reflected light. PLATES 3.2A - 3.6A show the reflected light micrograph mosaics, with scale bars indicated. The corresponding crack maps are shown in PLATES 3.2B - 3.6B. In each case, the long and short axes of micrograph and map are parallel.

FIGURES 3.18 - 3.22 present the Rose diagrams of crack number and density vs. orientation which correspond to each map. The horizontal axis of the semi-circular contours is parallel to the long axis of both map and micrograph in all cases. The insets provided show the orientation of the long (squares) and short (circles) axes for both map and micrograph.

PLATE 3.2. Thin section mosaic (A) and crack map (B) for specimen ABI.

FIGURE 3.18. Orientation data from PLATE 3.2B (ABI).

MAP# GAB1a
OF CRACKS= 310



RMAX= 27.343
CMAX= 3
MAP# GAB1a
OF CRACKS= 310

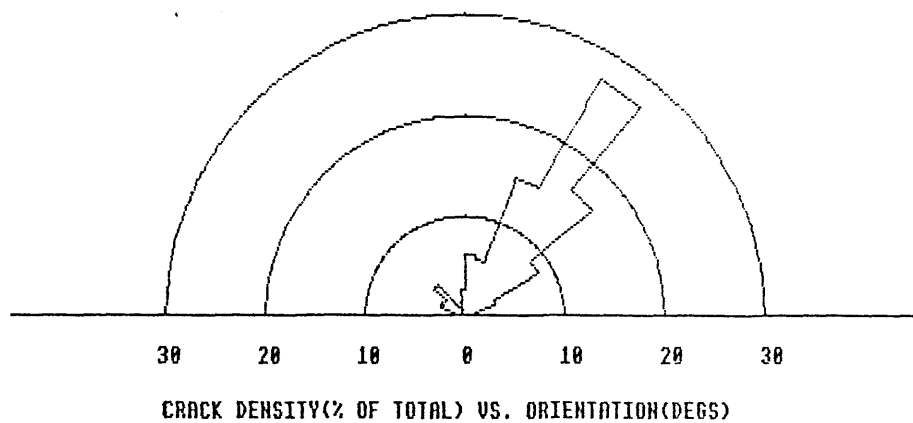


PLATE 3.2

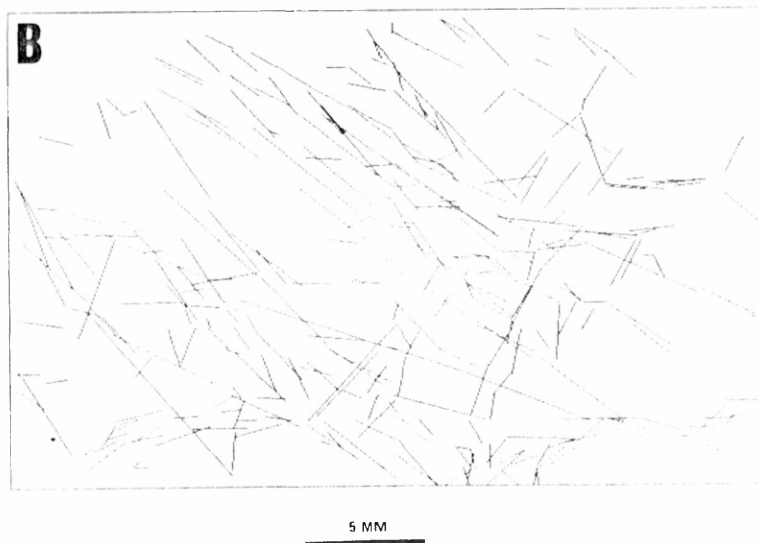
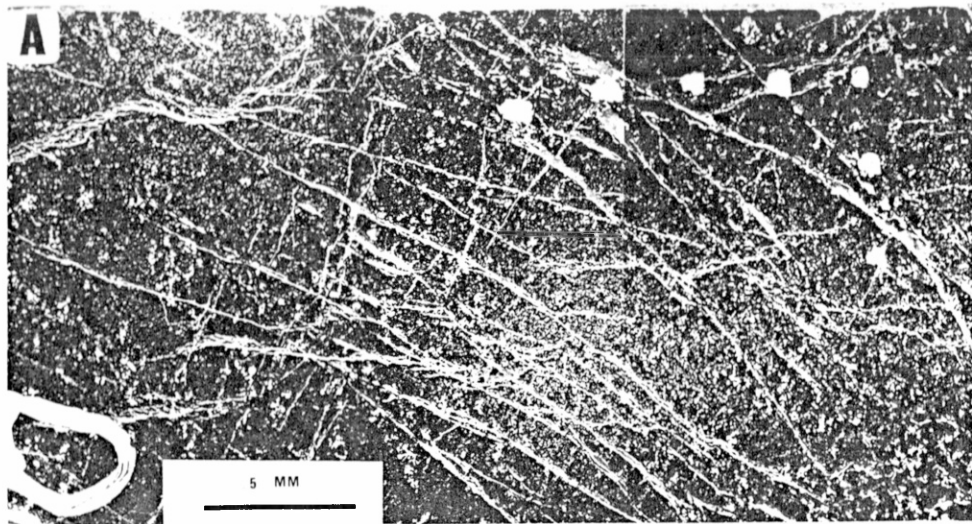
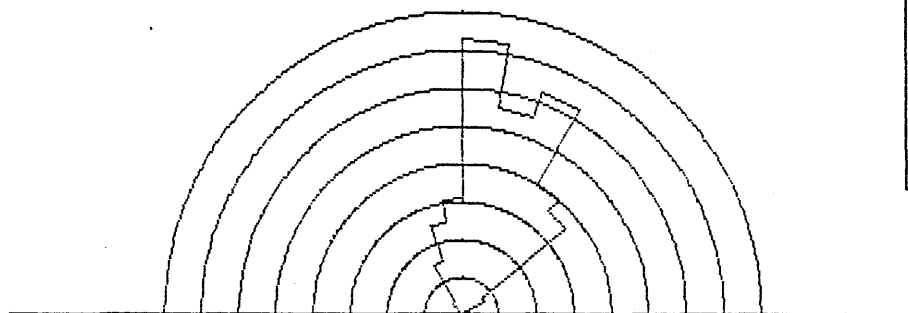
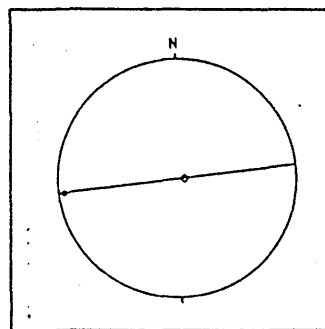


PLATE 3.3. Thin section mosaic (A) and crack map (B) for specimen ABIII.

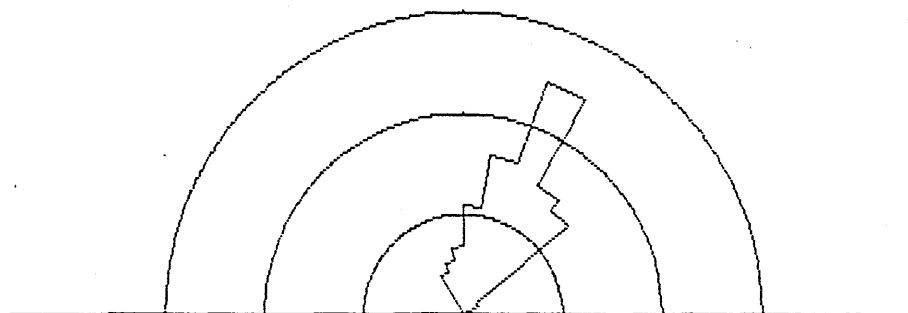
FIGURE 3.19. Orientation data from PLATE 3.3B (ABIII).

MAP# ABIIIa
OF CRACKS= 357



80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80

CRACK NUMBER VS. ORIENTATION(DEGS)



30 20 10 0 10 20 30

CRACK DENSITY(% OF TOTAL) VS. ORIENTATION(DEGS)

PLATE 3.3

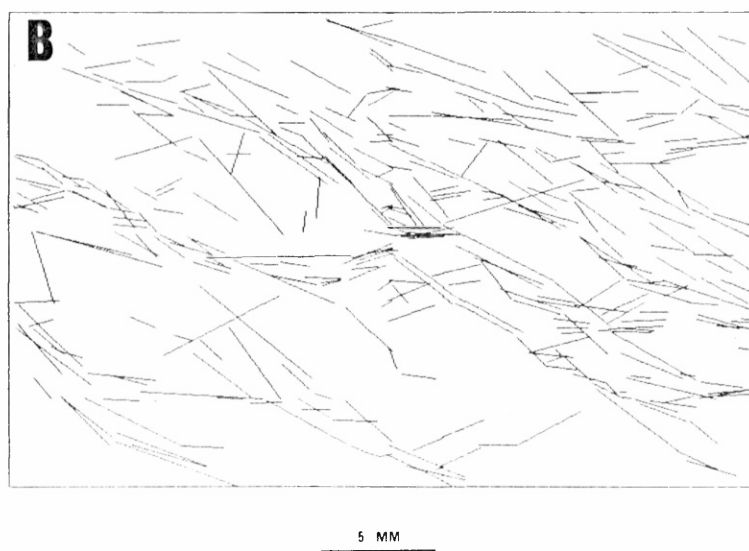
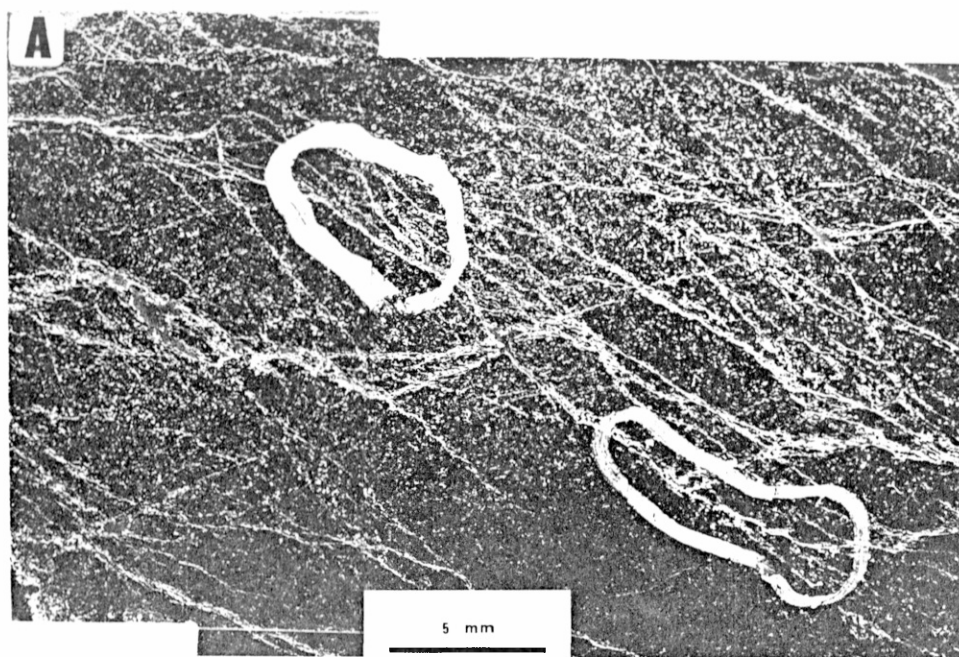


PLATE 3.4. Thin section mosaic (A) and crack map (B) for specimen AB18.

FIGURE 3.20. Orientation data from PLATE 3.4B (AB18).

MAP# GAB18a
OF CRACKS= 482

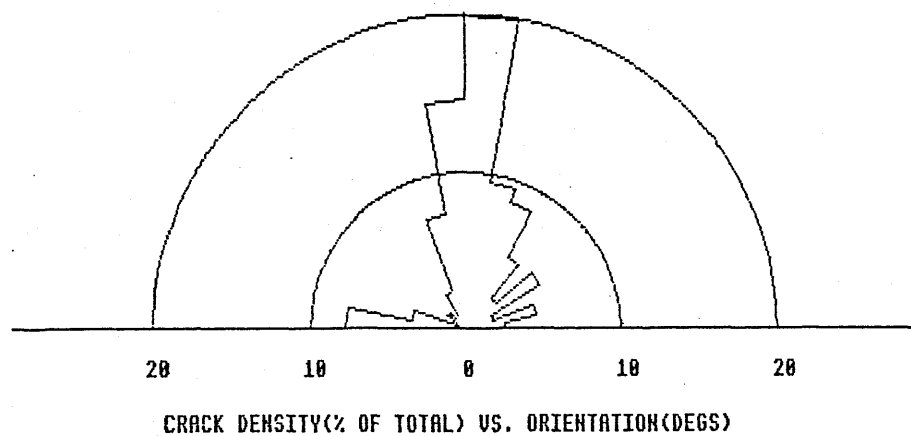
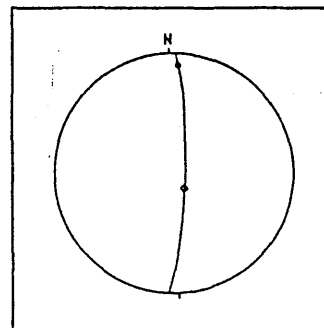
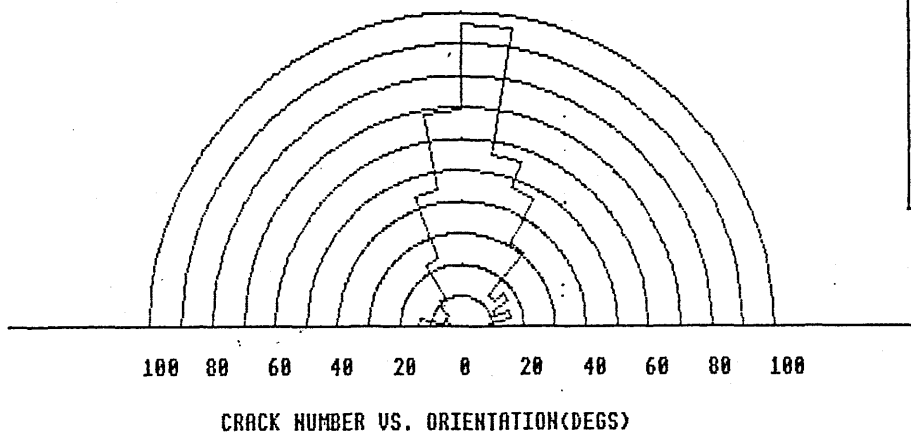


PLATE 3.4

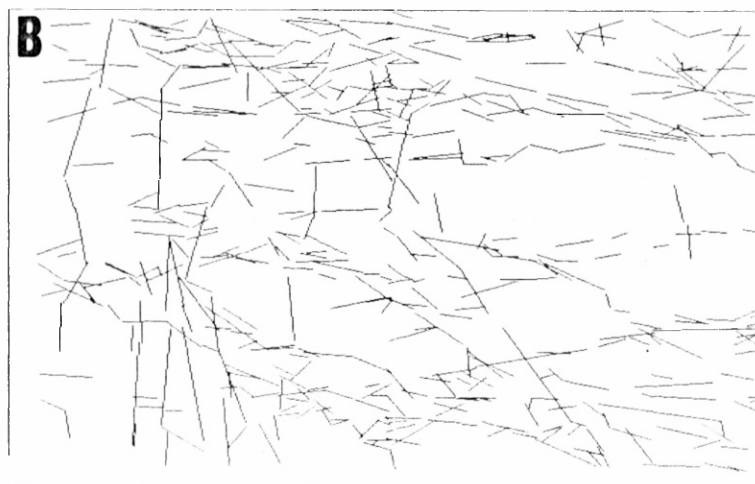
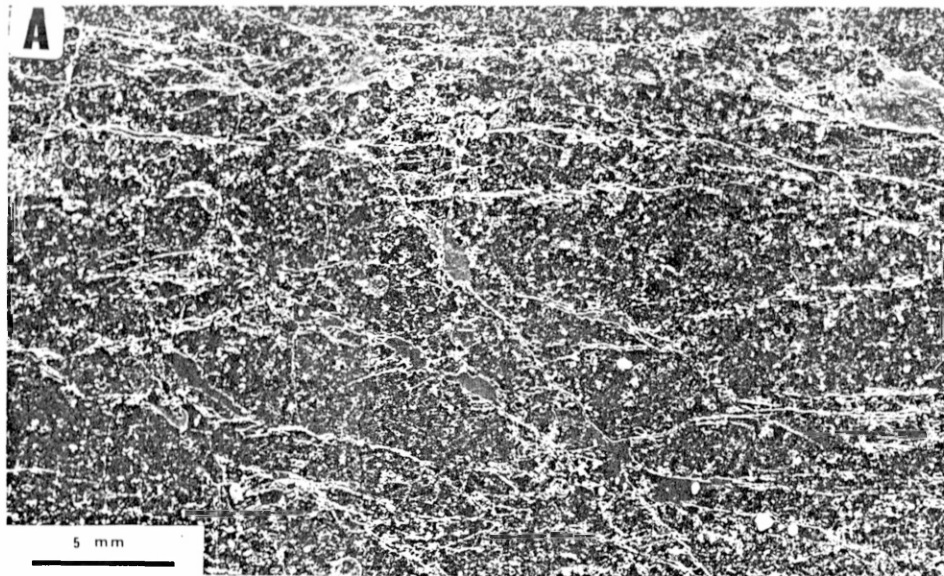


PLATE 3.5. Thin section mosaic (A) and crack map (B) for specimen OL2.

FIGURE 3.21. Orientation data from PLATE 3.6B (OL1).

MAP# GOL1a
OF CRACKS= 544

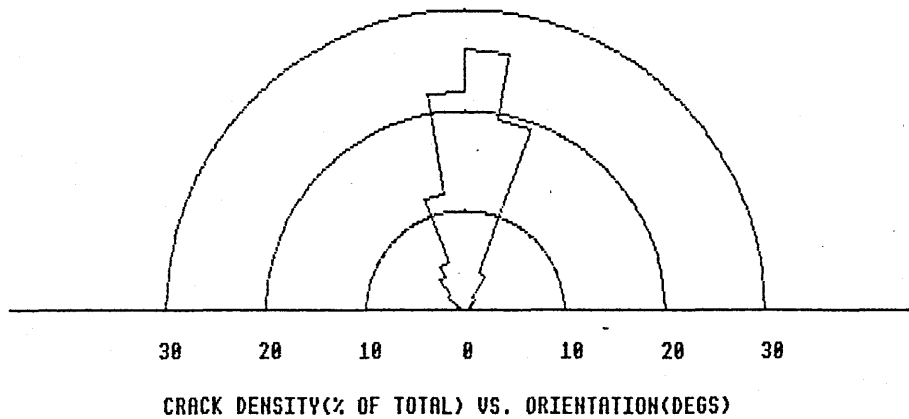
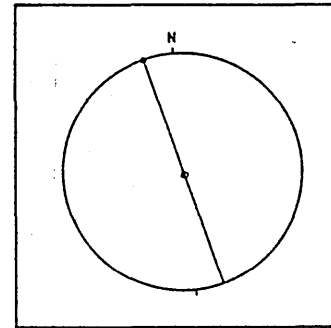
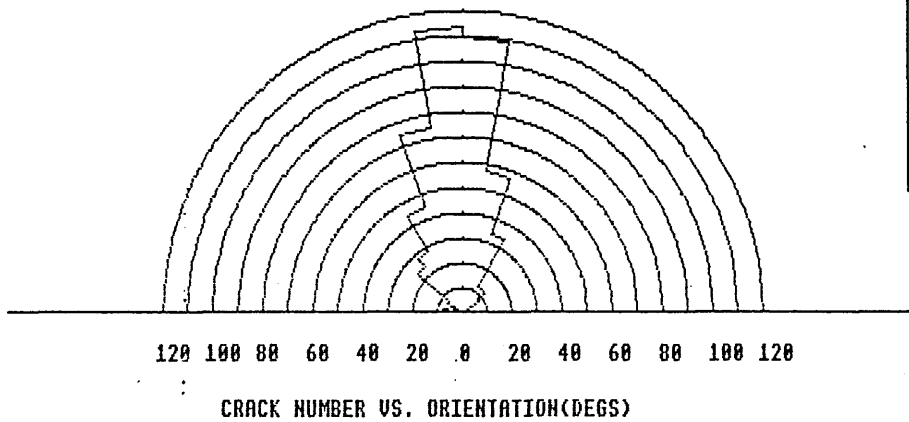
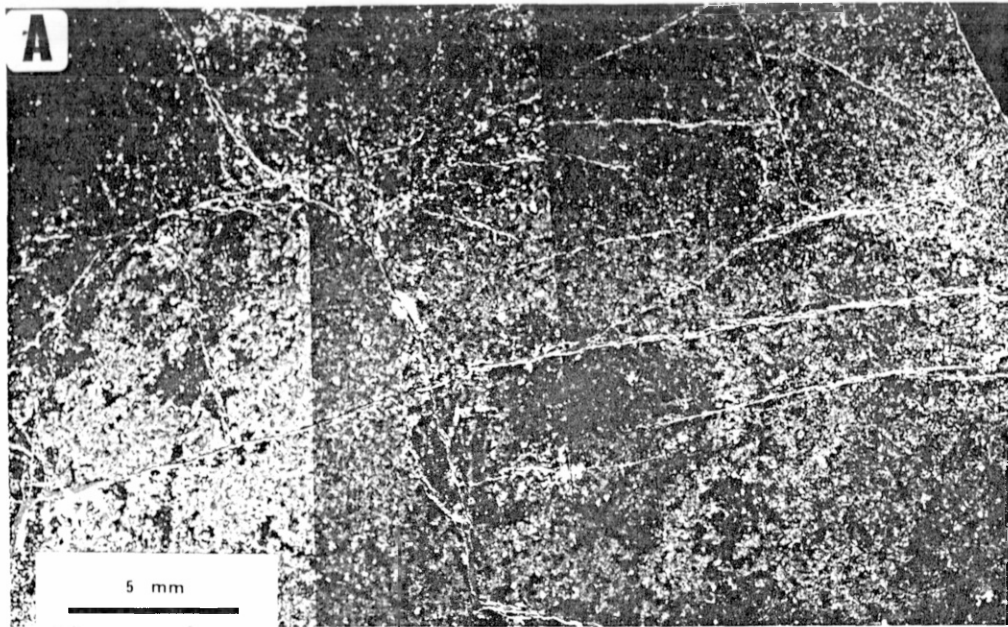


PLATE 3.5



5 MM

PLATE 3.6. Thin section mosaic (A) and crack map (B) for specimen OL1.

FIGURE 3.22. Orientation data from PLATE 3.5B (OL2).

MAP# 60L2a
OF CRACKS= 196

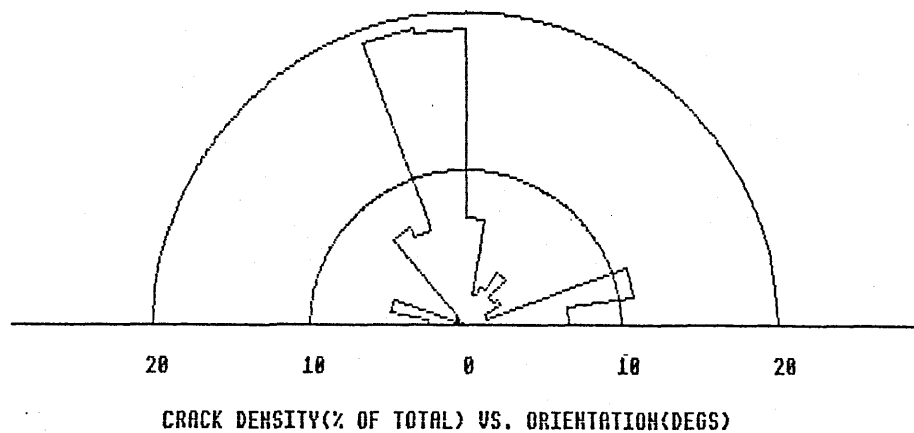
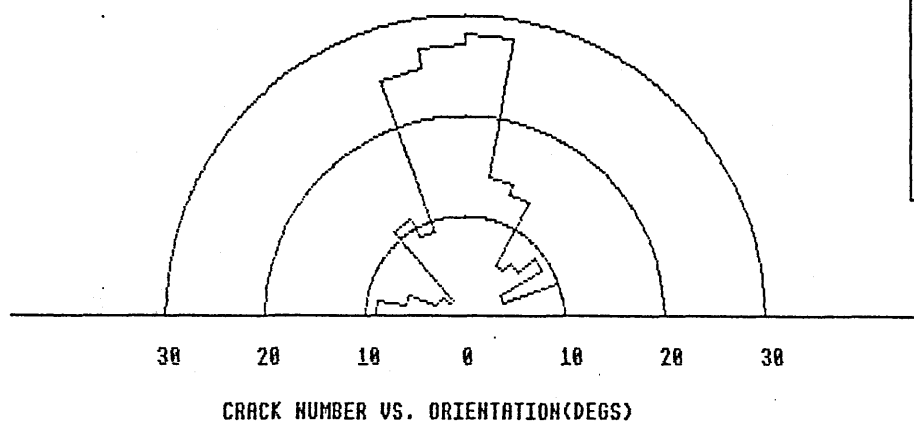
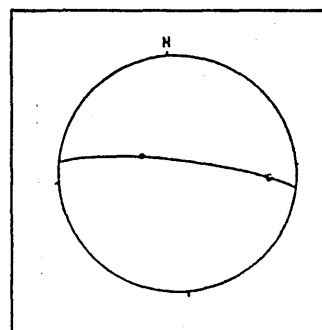


PLATE 3.6

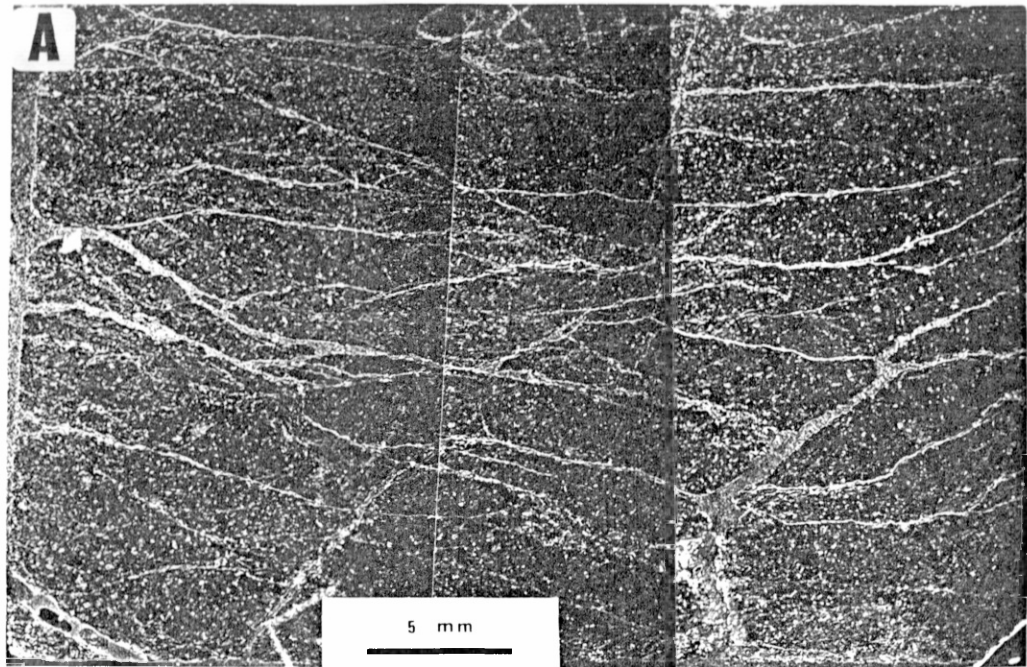
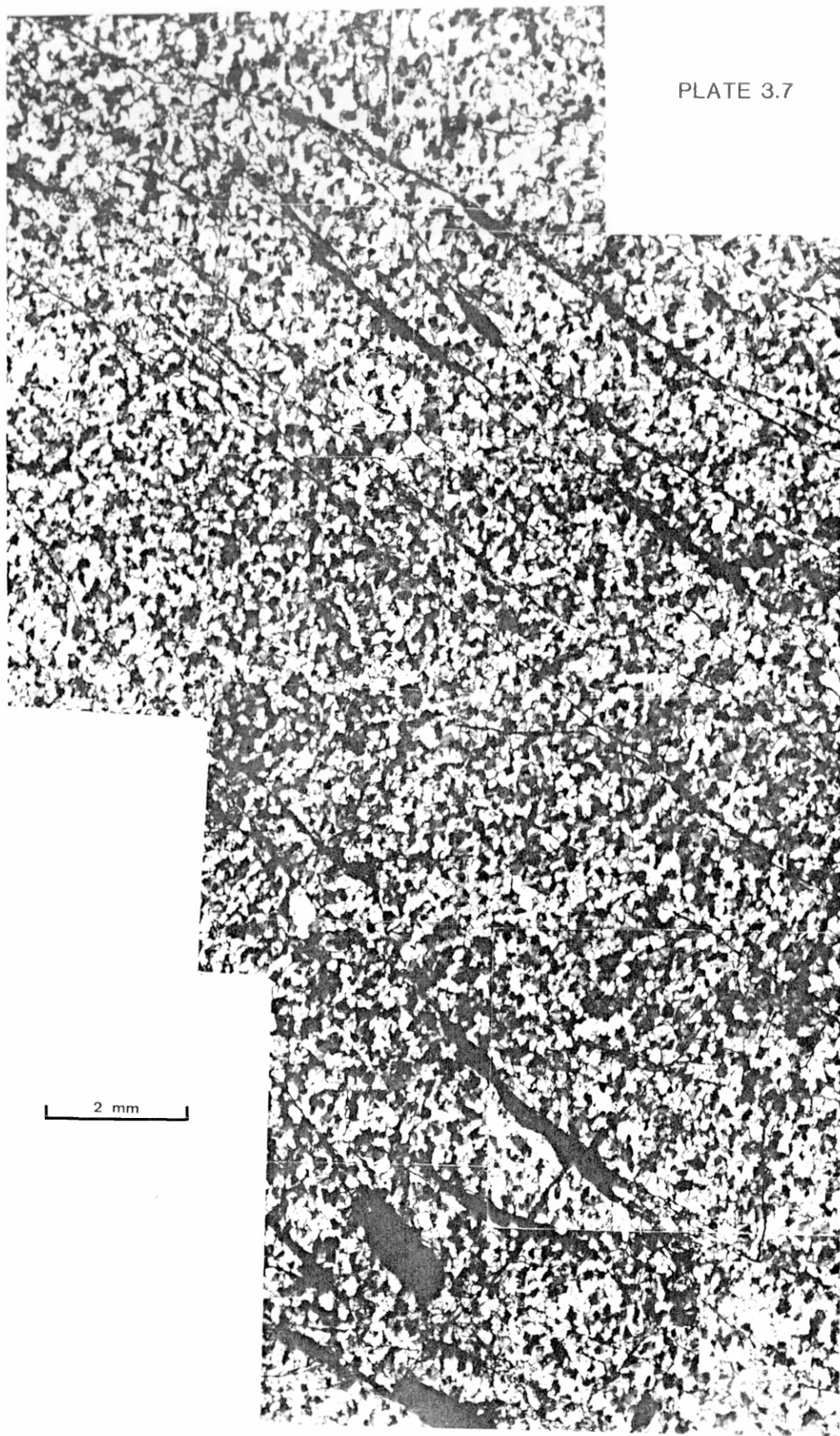


PLATE 3.7.

Photomosaic from specimen ABI. Area shown comprises the digitized crack mosaic map of figure 3.23. Long axis of photograph is oriented parallel to the long axis of the mosaic map.

PLATE 3.7



emphasized that the techniques developed in this study are not restricted to crack data alone. They can quite easily be modified to treat a range of problems involving two-dimensional morphological patterns on a variety of scales of interest to both structural geologists and rock mechanics workers alike.

3.3.4 DISCUSSION

All of the samples exhibit a degree of preferred orientation, a conclusion most strongly supported by the Rose diagram plots of crack density vs. orientation. In discussing the results, the following two important factors should be considered:

- (1) How does the orientation in the 2-dimensional sections relate to the 3-dimensional data discussed in section 3.2?
- (2) Are there important differences between the crack statistics generated from hand tracings of cut faces and those generated from thin section crack maps?

3.3.4.1 Relationship Between 2-D and 3-D Data

Blenkinsop (1982) described a method for obtaining 3-dimensional crack information from 2-dimensional sections. The technique requires the cutting of two perpendicular sections from a sample, and preparation of Rose diagrams of crack orientation for each section. The orientation of the section is then marked with respect to the known orientation of each sample. A great circle trace representing the plane of that section is plotted on an equal area stereographic projection, and marked at 10° degree intervals. The Rose diagrams are then transferred to the great circles, and the number of cracks in each 10° sector is recorded. Where a point maximum exists for each section, the plane of mean crack orientation can be traced onto the stereogram. Where more than one maximum exists for a section, these can be

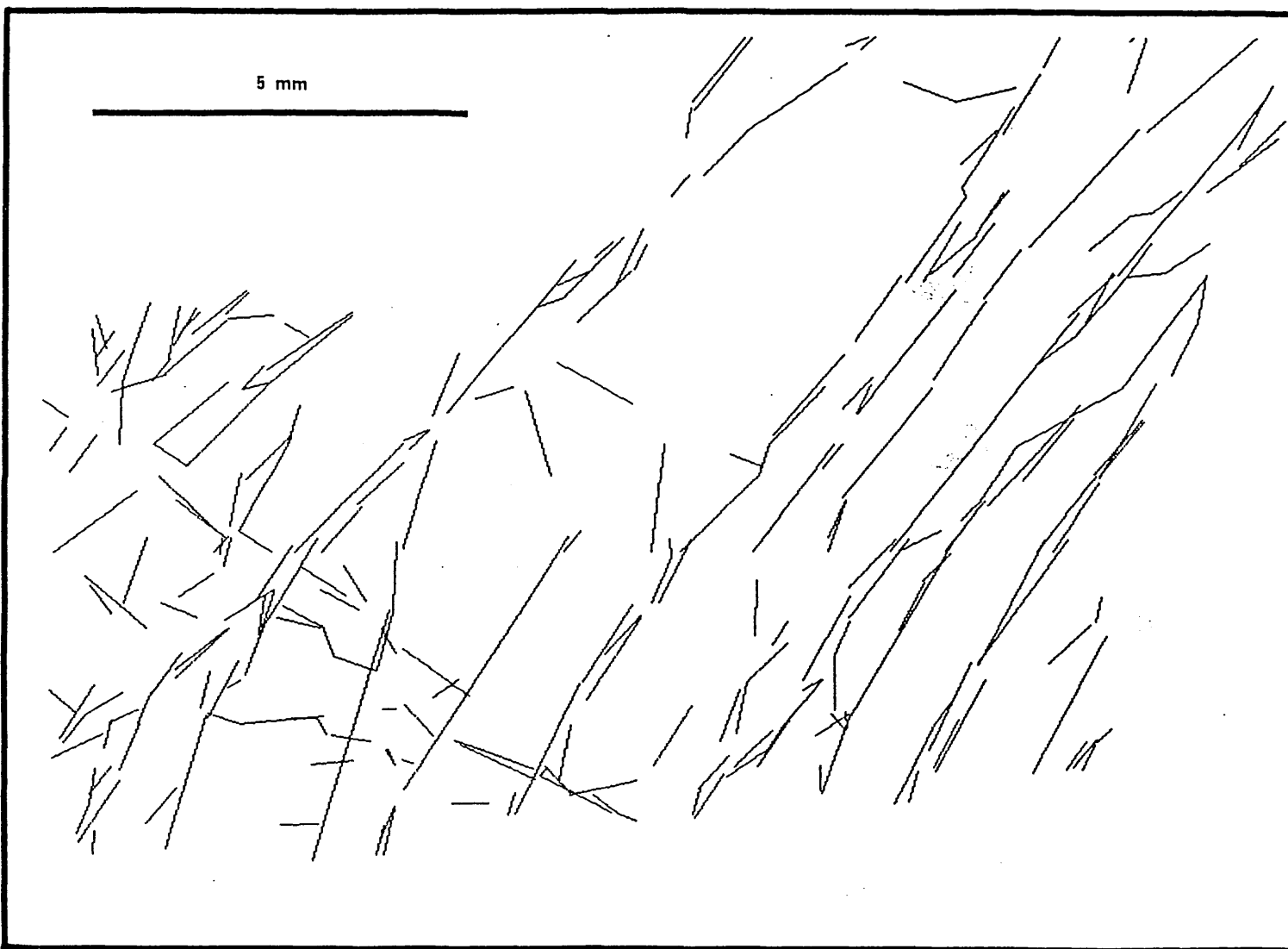


FIGURE 3.23. Mosaic crack map from photomicrograph in PLATE 3.7, comprised of 6 individual A4-sized maps linked together with programs WFCOR and MPLOTG (see Appendix 1). Long axis of map is parallel to that of PLATE 3.7.

treated as separate distinct sets of cracks.

I have already noted that sample limitations prevented the cutting of mutually perpendicular sections for most pebbles. Nonetheless, an attempt has been made to apply the same technique, because sections cut from different samples have a range of planar orientations. The mean fracture orientations at a given locality, as deduced from the 2-dimensional sections, can then be compared with the direct 3-dimensional measurements. The degree to which they correspond can be used to ascertain how closely the smaller scale cracks mimic the trends of overall fractures within the conglomerate unit.

Figures 3.24 through 3.27 summarize the results obtained. Figs. 3.24, 3.25 show a set of stereographic histograms for samples from Ablana, and Fig. 3.26 shows the corresponding results from Olloniego. Densities as a percent of total per 10° degree interval are color coded for easy identification, as described in the key accompanying each figure. The data are integrated in Figure 3.27. For each histogram sector whose density is at least 15% of the total for a sample, a point is plotted at the center of that sector. Data obtained from cut faces is represented by circles, and stars represent points taken from thin section measurements. Figure 3.27A represents the compilation from Ablana, and 3.27B records the results from Olloniego. For the purpose of comparison, the corresponding 3-dimensional data at these localities are shown in Figures 3.27C, D.

Results are clearly equivocal. The data distribution from Olloniego agrees well with the 3-dimensional measurements. The plane marked "M_o" in figure 3.27B is the inferred mean fracture plane from the Olloniego locality, obtained by treating the highest point concentration as the mean pole orientation. It corresponds well with the distribution of 2-D maxima. Unfortunately, no such correspondence exists for the data from Ablana. Here, point maxima show less tendency to lie along a single plane, and there is a great discrepancy between the general orientation of these maxima and the mean 3-D inferred fracture plane (M_o). If one were to infer a mean fracture trend from the 2-D data alone, it would lie at nearly right

FIGURES 3.24 - 3.26. Stereographic histograms from the Rose diagrams of crack density vs. orientation in figures 3.9 - 3.22. For a description of stereographic histograms and the technique used in their preparation, see text (section 3.3.4).

FIGURE 3.24. A. AB1
 B. AB3
 C. AB13

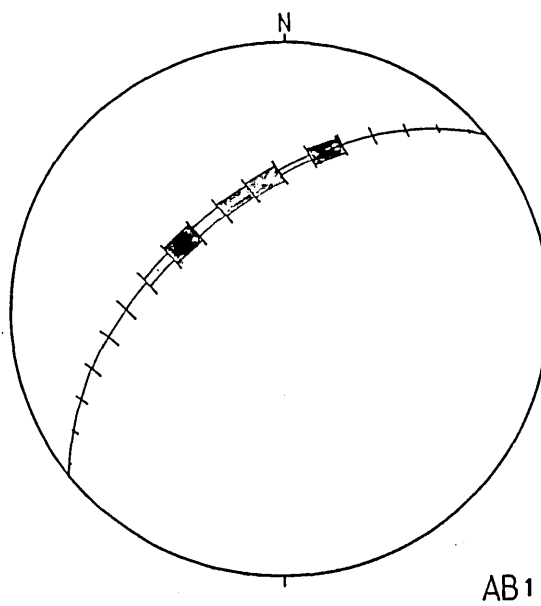
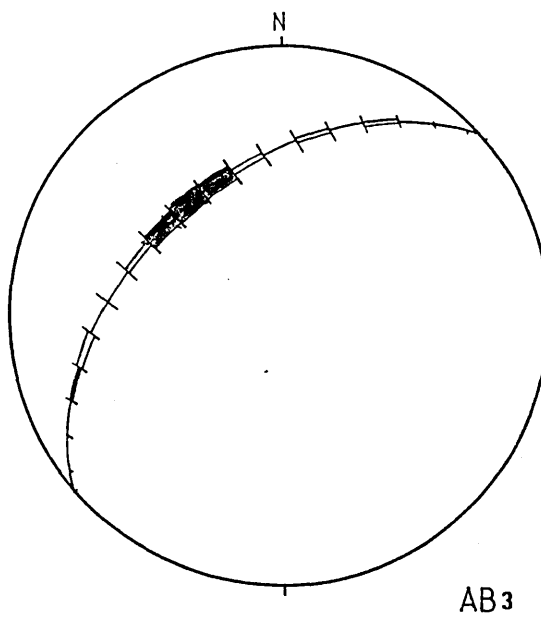
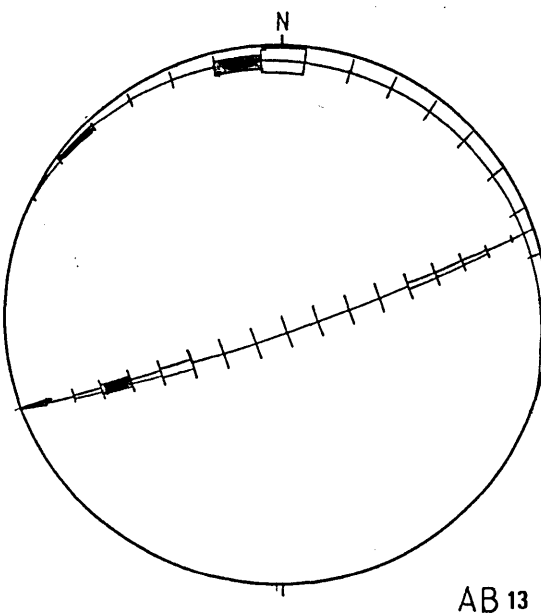
FIGURE 3.25. A. AB18
 B. ABI
 C. ABIII

FIGURE 3.26. A. OL1
 B. OL2
 C. OL3

Each 10 degree sector (corresponding to a 10 degree sector on the Rose diagram plot) is color coded according to the value for crack density as a percent of total area attached to it. Coding follows the following key:

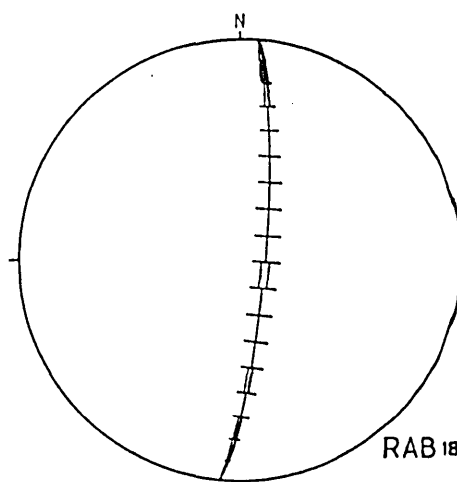
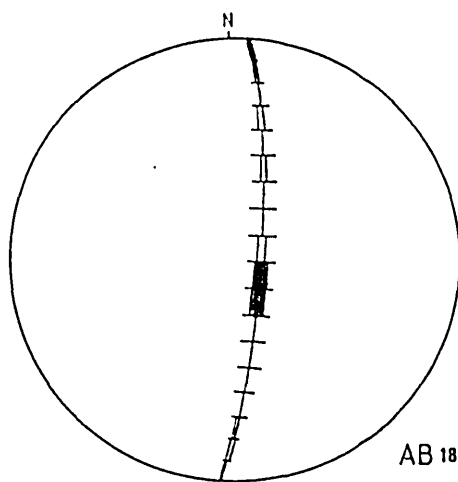
0	-05% of total	no color
5	-10% of total	green
10	-15% of total	red
15	-20% of total	blue
	>20% of total	yellow

3.24

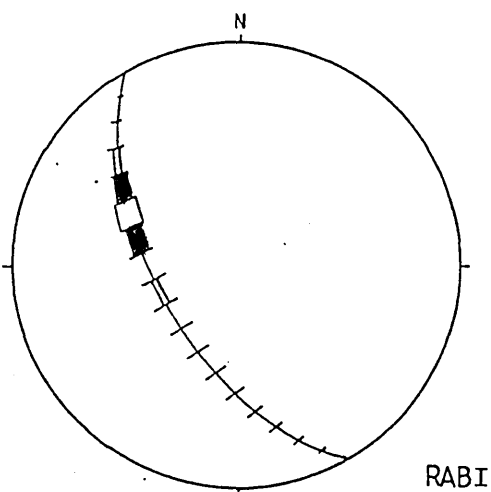
A**B****C**

3.25

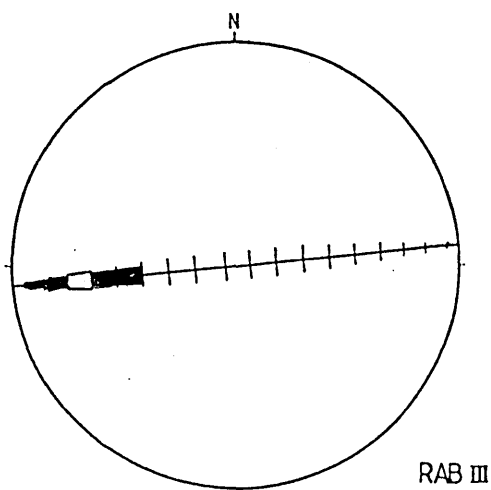
A



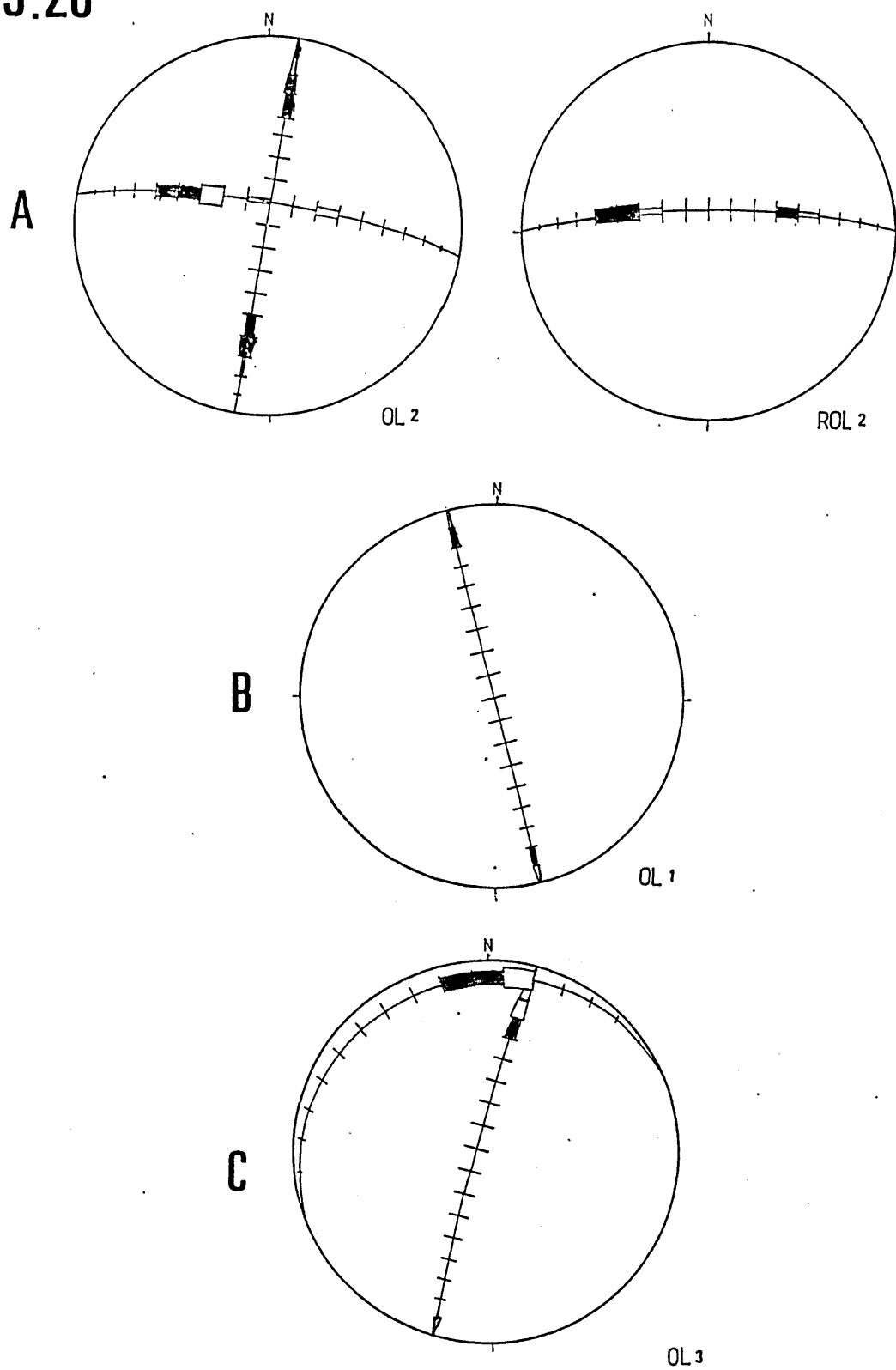
B



C



3.26



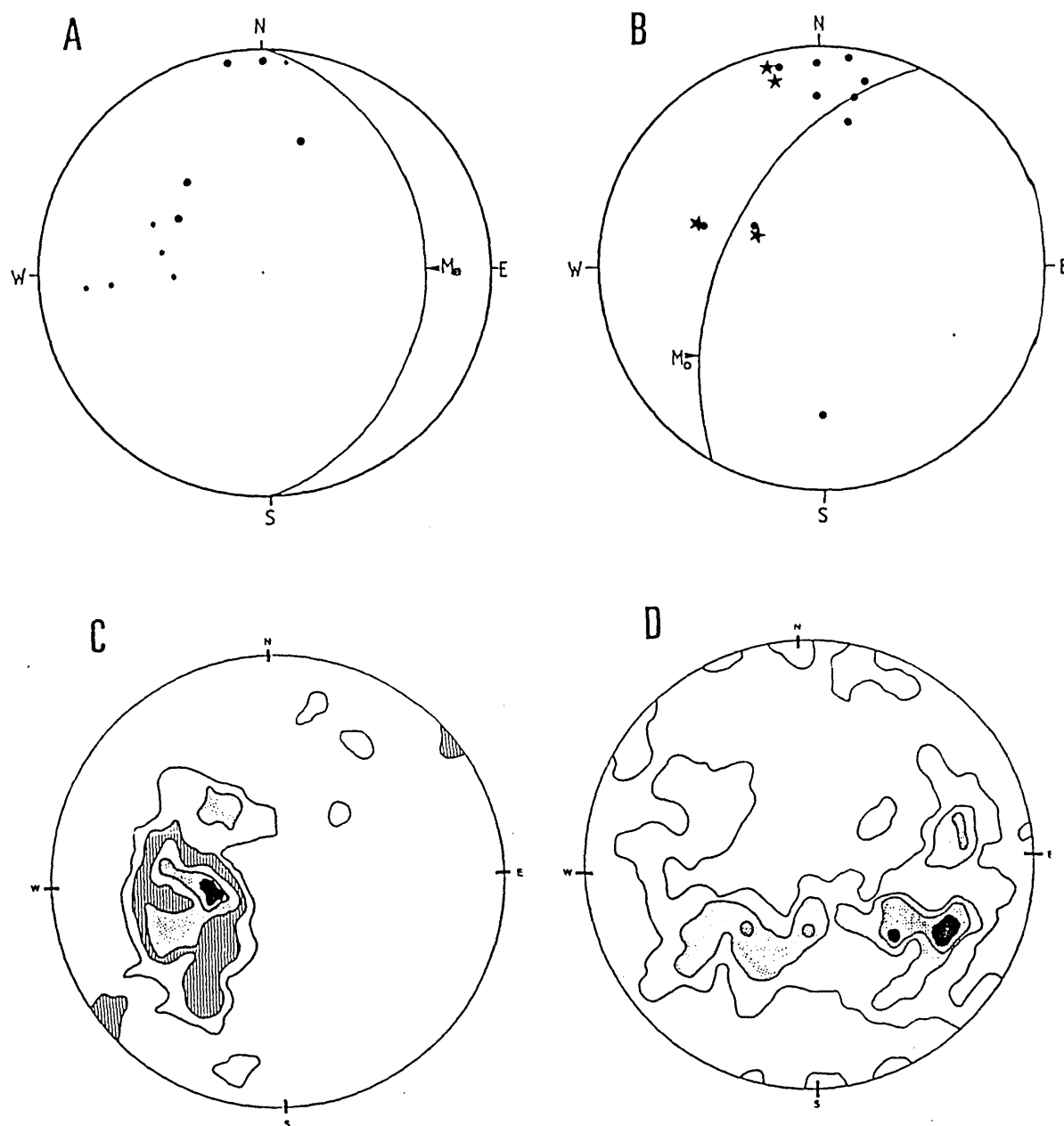


FIGURE 3.27. Integrated data from 2-dimensional crack analysis. (A) Ablana; (B) Olioniego. The centers of stereographic histogram sectors with densities of >15% of total area are plotted, with stars representing data from thin sections and dots indicating data from crack traces. For each locality, the mean fracture plane as inferred from the 3-dimensional results of figure 3.1 are drawn (M₁, M₂). The degree to which points cluster along that trace is a measure of how closely the two data sets coincide. Equal-area projections of poles to fracture planes from Ablana (c) and Olioniego (d) are shown for comparison (as in figs. 3.1a, 3.1c respectively).

angles to the 3-D measurements. Small sample size might account for the discrepancy; 4 of the 6 samples for which 2-dimensional data was gathered at Ablana come from the group of rocks comprising the fracture map of figure 2.5A. All come from the same area of the map, and 3-dimensional data recorded on the map shows that the dominant fracture trends in that set deviated considerably from the orientation of the point maximum for the locality as a whole. More samples are obviously needed to test whether these local orientation deviations commonly occur at a given locality.

It should be stressed that the agreement of the two separate data sets from Olloniego is encouraging. In many naturally deformed rocks, it is not possible to gather meaningful 3-D crack data from field observations. That data is vital if relationships between microscopic failure mechanisms and larger scale brittle features (e.g. joints, fractures, and faults) are to be ascertained. The use of perpendicular 2-dimensional sections and a microcomputer with digitizing facilities allows for rapid determination of orientations from a large number of samples and should enable reliable analyses of large data sets to be made in relatively short periods of time.

3.3.4.2 Comparison Between Cut Face and Thin Section Data

Orientation statistics appear to be relatively free of deviations resulting from the varying scale of observations, at least within the range studied here. One might expect that cracks visible to the naked eye would cover a broader range of orientations than the microcracks, and this is indeed true. It is evident from observations on just a few pebbles that, while one or two contact points may produce the majority of cracks in a pebble, some cracks generally originate from all contacts. At a microscopic scale, there are commonly more cracks in the dominant orientation, as shown in figures 3.24-3.27 (where measurements were made from the same plane from both cut faces and thin sections, they have been presented as a

pair). The general distributions, however, are similar. The fact is important, because of the need to analyse relatively large sample sizes to make accurate paleostress inferences. Since considerably less work is required to gather data from hand specimens, they may prove a valuable tool in large-scale studies.

3.4 CRACK LENGTH ANALYSIS

In section 3.3 I discussed the difficulty of obtaining meaningful length statistics without the use of nodal variables in the petrostructure analysis program. Even with nodal variables, the person who performs the actual measurements (or establishes the decision criteria for the computer program) must make arbitrary decisions concerning what will be called a crack. I have noted the hierarchical nature of crack systems as viewed at different magnifications. A similar hierarchy must be imposed when making crack length measurements. On the scale of individual grains, several authors (Hadizadeh, 1980; Dunn et al., 1973) have noted a direct proportionality between microcrack length and amount of permanent strain as determined from rock deformation experiments. While much of that variation in length is indeed attributable to varying degrees of inelastic deformation, lengths are probably also controlled by the presence of smaller scale crystallographic features (e.g. point and line defects, crystallographic cleavages). When studying transgranular cracks one might measure length as the distance of a segment which appears straight at a given magnification (which is essentially the measure obtained by using the MRL technique). That measurement might give an indication of the distance over which a crack will grow before it meets a barrier, but probably bears no direct relation to the amount of permanent strain. Straightness when viewed under magnifications of between 500x and 1000x might be determined by the spatial distribution of micropores or other small scale structures. At 50x, it will more likely appear to be controlled by the orientations of grain boundaries. If one attempts to measure length as the

sum of linked segments, the determining factor will invariably be the size of the pebble itself, since many such linked segments transect entire pebbles.

These considerations help to explain the uniformity of the crack length data obtained in this study. Figures 3.28, 3.29 show length histograms for the hand-traced specimens. Each histogram is strongly skewed towards small crack sizes with median lengths ranging from 2 to 4mm. Each pebble contains a few long cracks (>25mm), but in all specimens, no crack transects an entire map. In each case, however, linked networks of cracks run the entire length of a pebble, and these probably formed in a continuously propagating sequence. The presence of inhomogeneities (e.g. grain boundaries, pores, and other cracks) clearly causes deviation of propagation paths, but in most cases these barriers are not sufficiently strong to arrest crack growth.

Length distributions in cracks mapped from thin section micrographs reveal a similar pattern (fig. 3.30), but measured average lengths clearly decrease as magnification increases. Specimens showing the least pervasive deformation (OL2, AB18) are generally the least strongly skewed towards the smaller crack sizes, while the most intensely deformed specimens (ABIII, OL1) show the greatest percentage of cracks in the 1 to 2mm range. This reflects the relative densities of crack networks. In the most severely deformed specimens, cracking is pervasive, and interference within closely spaced crack arrays breaks the specimen into successively smaller blocks. In the least deformed specimens, long cracks propagate unhindered for greater distances before their paths are affected by neighboring crack segments.

In summary, specific criteria should be used to decide upon an appropriate size classification for a "crack" or cracked segment. In weakly cemented sands, where intragranular cracks predominate, individual microcracks can be used for comparison with experimentally deformed rocks with similar initial microstructures (Blenkinsop and Rutter, 1985). Rocks showing dense arrays of long transgranular cracks have no real experimental analog. Criteria which might be useful in unraveling their

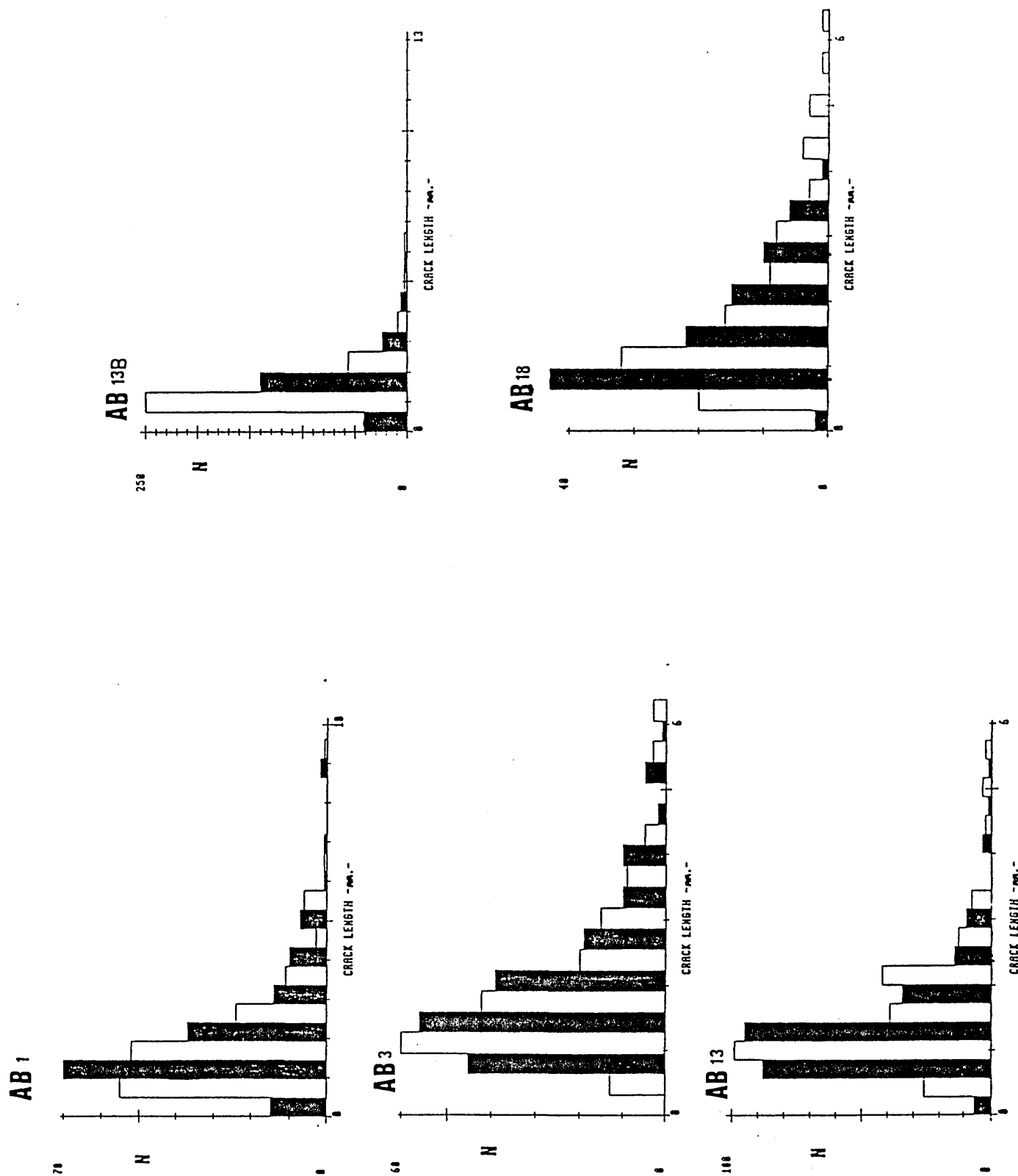


FIGURE 3.28. Length histograms of crack traces from hand specimens at Ablana; N = crack number.

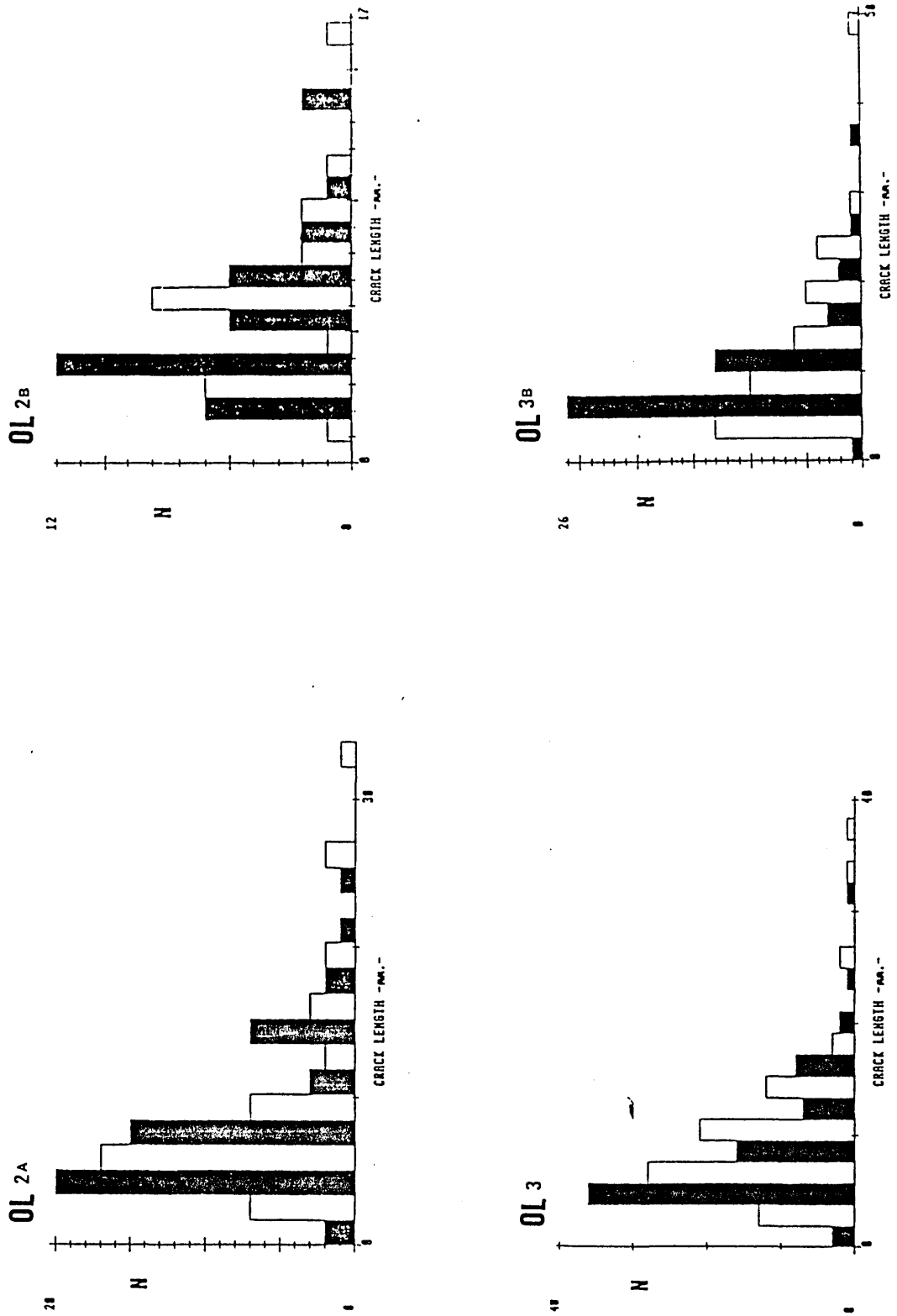


FIGURE 3.29. Length histograms of crack traces from hand specimens at Olloniego; N = crack number.

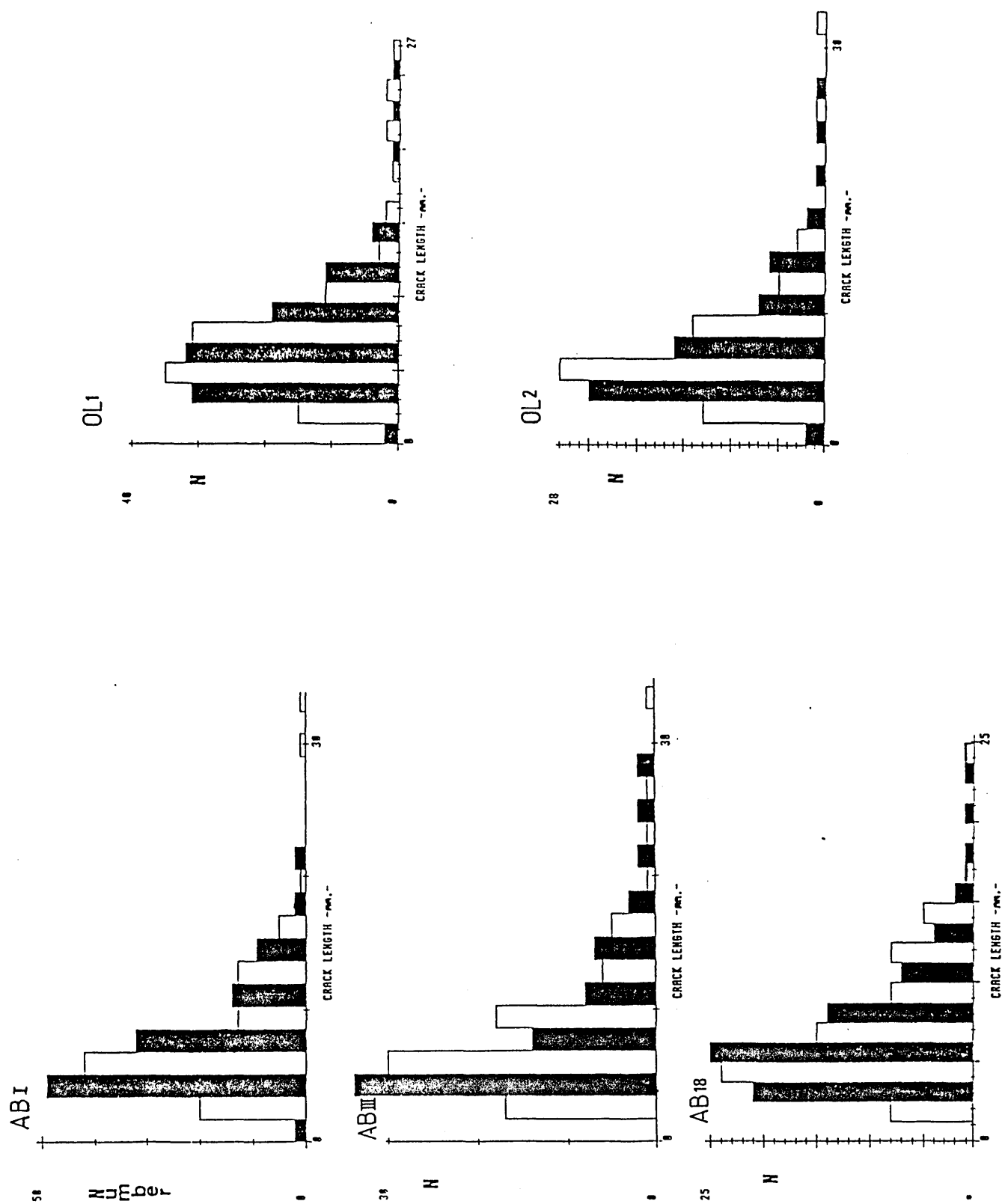


FIGURE 3.30. Length histograms from crack traces viewed in reflected light at 11x magnification; N= crack number.

deformation histories will be further discussed in the next chapter.

MICROSTRUCTURES IN DEFORMED PEBBLES

4.1 INTRODUCTION

In previous chapters of this thesis, I have made continued comparisons between the macroscopically visible fracture networks within the Mieres conglomerate and crack behavior observed in granular aggregates on a much smaller scale, as reported from studies in the field of experimental rock deformation. The continuum nature of individual pebbles has been emphasized, and little attention has been focused upon microstructural aspects of pebble deformation. These comparisons have proven quite useful in characterizing the overall brittle response of the entire pebble aggregate, particularly in relation to both the applied tectonic stress field and the local stress fields arising at point contacts. Scale-dependent limitations, however, have also been noted; in large part these arise because each pebble is itself a complex polycrystalline aggregate. The mechanical response of a group of pebbles to the load applied at its boundaries is determined by a range of microstructural variables (e.g. mineralogy, grain size/morphology/distribution, porosity, degree of flaw heterogeneity, microcrack density/distribution), and not simply by the distribution of stresses arising from pebble-to-pebble contacts. In this chapter, the importance of these variables will be discussed, in an attempt to characterize the mechanisms of failure within individual pebbles. Microstructural characteristics will be described in detail, and these will serve as a basis for comparison with experimentally-produced microstructures reported by various authors.

All samples studied showed some evidence of crystal plastic deformation - generally the development of undulose extinction in quartz - but this is seen in both uncracked and highly cataclased specimens. It is therefore inferred to be a relict feature derived from the parent sandstone material. All other microstructural evidence suggests that deformation within the pebble unit occurred by

dominantly cataclastic processes. Very briefly, cataclasis involves the change of shape of a rock mass by micro- or macrofracturing, with accompanied sliding between particle interfaces. Rutter (1985, in press) subdivides failure by cataclastic processes into two categories, based on homogeneity of flow considerations. It can occur as a localized phenomenon (cataclastic faulting), in which sliding occurs along a planar zone containing intensely crushed material. Outside of that zone, the intensity of cracking is greatly reduced, and the rock appears largely intact. Cataclasis can also occur without significant localization, in which case the rock may be said to have deformed by cataclastic flow. At temperature and pressure conditions too low for crystal plastic processes to be operative, distributed cracking can result in homogeneous flow on the scale of a hand specimen or larger. Cataclastic flow can then be characterized as a ductile phenomena, where ductility is defined as the capacity for homogeneous flow in a material. It is important to emphasize that a scale of homogeneity must be delineated when ductility is considered. Microstructural observations on specimens deformed during laboratory tests often point to the occurrence of distributed microcracking on the grain scale (e.g. Scholz, 1968; Sangha et al., 1974). Similar textures can be seen in naturally deformed rocks, although a class of behavior is often seen, particularly in rocks which have undergone folding, in which long transgranular cracks bound relatively undeformed, polygonally shaped polygranular fragments of centimeter dimensions (e.g. Hadizadeh and Rutter, 1983; Blenkinsop and Rutter, 1985, in press). This type of distributed cataclasis is not observed in laboratory studies, because specimen size is usually restricted to very small dimensions by the nature of the test apparatus. Figure 4.1 presents a diagrammatic illustration of the relationship between cataclastic faulting, cataclastic flow, and intracrystalline plasticity, after Rutter (1984, in press). It emphasizes the sensitivity of transitions between the different processes to variations in strain, temperature, and pressure.

A primary objective of the present microstructural

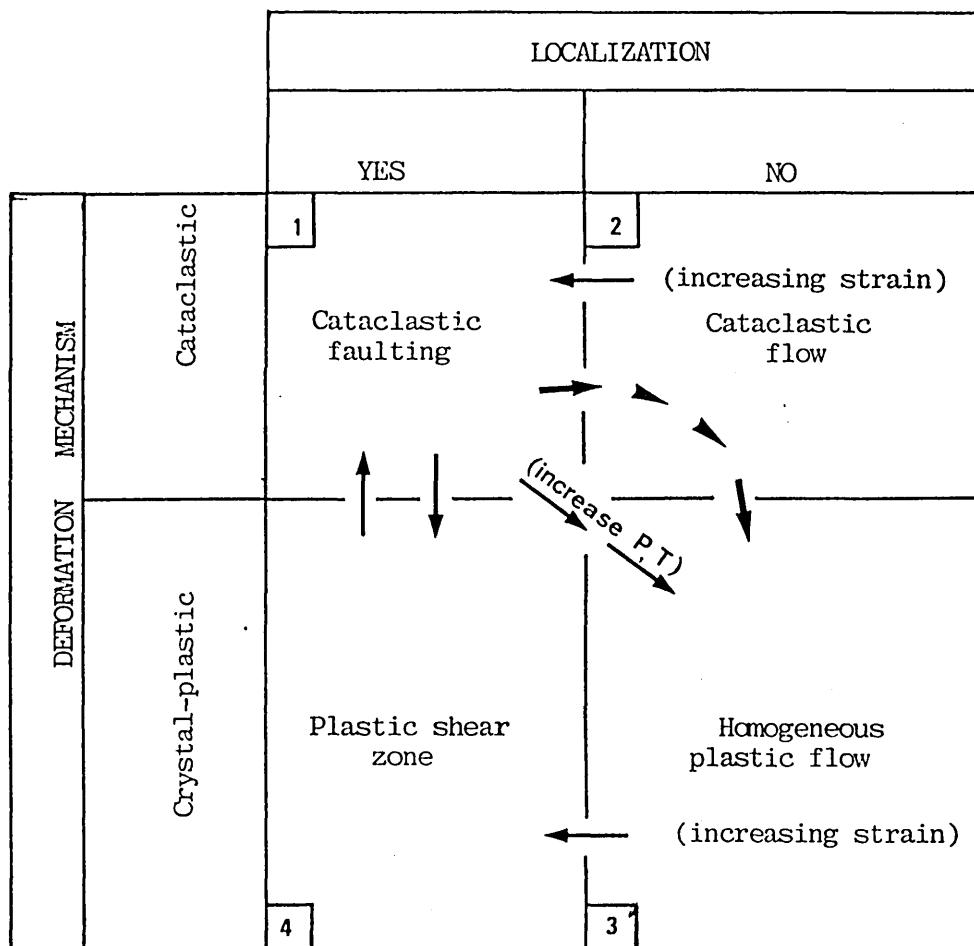


FIGURE 4.1. Diagrammatic representation of mode of failure transitions in rocks, showing how the description of mode of failure depends on both the operative deformation mechanism and degree of localization. Deformation mechanisms are grouped into those involving dilatancy (cataclasis) and those not involving volume change (crystal plasticity in the loose sense). After Rutter, 1984.

study is to determine criteria which might help to characterize the transition from localized to distributed cataclasis in the quartzite pebbles of the Mieres conglomerate. To a good approximation, the conglomerate unit can be viewed as an "open-air" rock deformation laboratory, since examples of pebbles loaded at both ends and confined along their long axes by contacting pebbles abound. Most pebbles are at least an order of magnitude larger than the typical laboratory specimen. Nonetheless, they experienced a set of applied boundary conditions closer to those imposed on cylinders loaded in a triaxial rock deformation apparatus than to most stratified sedimentary deposits. Provided that cracking resulted in response to slow loading from the overlying thrust, and not from elevated stresses associated with seismic faulting, one would expect that the strain rates imposed upon the pebbles were both slower and of longer duration than those obtainable in the laboratory. Over a range of samples, it may be possible to trace the microstructural evolution from pre- to post failure stages, and thus test assumptions concerning the effects of variables such as specimen size and strain rate on failure behavior.

4.2 MICROSTRUCTURAL DESCRIPTION

4.2.1 Starting Material

In hand specimen, each of the pebbles studied appears compositionally identical: the quartz is uniformly gray in color, and individual grains cannot be distinguished with the naked eye. Cracks are easily identified on clean surfaces, since many are open and show a slight discoloration. In thin section, however, they are seen to be relatively pure (>90% qtz.) orthoquartzites with average grain sizes ranging from 50-300um. In addition to variations in sorting and angularity, the range of samples studied exhibits small but significant variations in cement properties, primarily in the amount of argillaceous cement filling interstices between grains. Plate 4.1A is a transmitted light micrograph of an uncracked portion of

PLATE 4.1 -Optical photomicrographs from transgranularly-cracked samples.

A. Initial microstructure of specimen AB13.

B. Initial microstructure in reflected light. Grain boundaries are sometimes delineated by aligned microcavities (arrows). Scale bar = 200um.

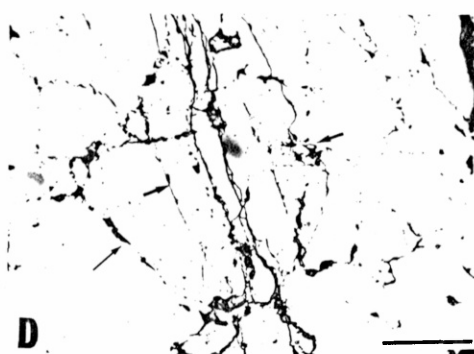
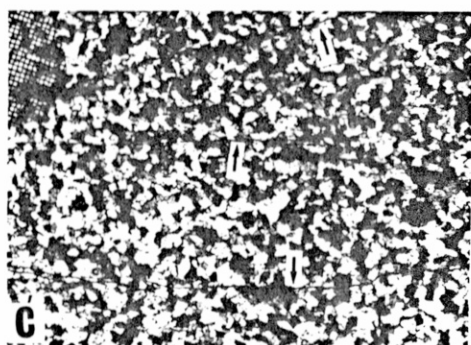
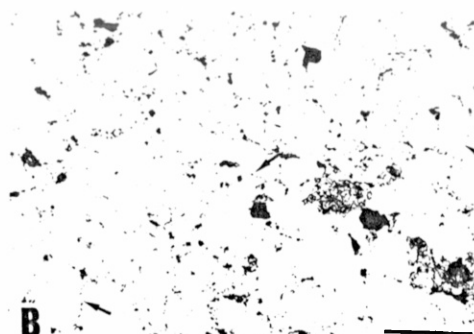
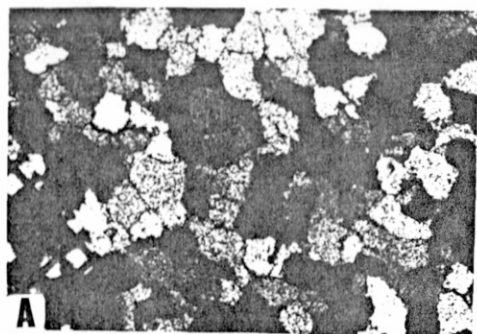
C. General appearance of transgranular cracks (arrows) in cross polarized light.

D. Reflected light view of transgranular cracks. Short arrows isolate zone of cracking, and long arrow points to cracked grain boundary. Scale bar = 200um.

E. Higher magnification mosaic of transgranular crack segments. Scale bar = 500um.

Except where indicated, circular steel grids are used for scale in all cross-polarized optical photomicrographs. The grid used has a diameter of approx. 3mm, and each square has approximate dimensions of 100um x 100um.

PLATE 4.1



sample AB13, and it illustrates the general appearance of the undeformed microstructure.

Optical (both transmitted and reflected light) microscopy and SEM techniques were used to study structures developed in the deformed rocks. Reflected light proved an especially useful tool, because of the particular texture of the starting material. Most rocks are equigranular, and consist of very straight grain boundaries (except where pressure solution between grains produces a sutured shape). The texture arises from partial cementation of sub-spherical detrital quartz grains by an optically continuous quartz overgrowth cement. Where interstices between grains are incompletely filled, small voids exist which help to delineate the boundaries of individual grains. These are clearly visible using reflected light on polished surfaces (Plate 4.1B). In samples which contain a noticeable amount of argillaceous cement, diagenetic reactions at grain boundaries serve to accentuate pore spaces. Hadizadeh (1980) observed similar textures in samples of Oughtbridge gannister, from the Coal Measures of northwest England. He concluded that fine mechanical polishing was the preferred method of preparing specimens which contain such quartz overgrowths, since the process of ion-etching (discussed in Chapter 3, section 3.3) preferentially damaged the overgrowths, thus rendering distinctions between cracked and uncracked grain boundaries impossible to make.

When characterizing the initial microstructures of undeformed samples, experimentalists generally report a range of quantitative measures of physical properties, which include mean grain diameter, mean pore size, and effective porosity. In this study, I have decided to qualitatively describe differences between these variables (see Table 4.1), in lieu of performing quantitative measurements on each sample. In part, this stems from time constraints which have arisen in the latter stages of this work. In addition, however, the decision is based on the recognition that the microstructure of even relatively uncracked zones of a given specimen may not provide an accurate assessment of the microstructure prior to deformation. Post-crack cementation is evident in many

samples, and some sections show features indicative of a complex interrelationship between cracking and cementation events, as documented by Blenkinsop in the Moine quartzites (1982). Any attempt to infer quantitative relationships between crack characteristics and sedimentological variables measured after a prolonged period of diagenesis seems misguided. The approach taken here has been to compare crack statistics from thin section analyses with similar statistics from published experimental data, in an attempt to infer physical parameters at the time of deformation.

4.2.2 MODES OF FAILURE

The samples studied exhibit a surprisingly wide range of failure behavior, considering the relatively small number of specimens collected for study. The variation between samples can be classified according to the extent of visible damage, as measured by (a) the density of fractures observed in a given section, (b) the intensity of deformation along individual microfaults (based on observations on the amount of grain size reduction and corresponding widths of the affected zone), and (c) the proportion of a given section visibly unaffected by deformation. Using these criteria, the nature and degree of localization along faults can be assessed, and the extent to which deformation within a sample is distributed can be examined.

4.2.2.1 Transgranular Cracking Along Discrete Surfaces

In all thin sections, long transgranular cracks which transect several grains are observed. In some specimens, however, they are the only visible signs of deformation. These generally show a tendency to align in subparallel networks, and spacing occurs on the scale of a few to ten millimeters. In detail, the crack paths are wavy; they commonly propagate both along grain boundaries and through individual grains. In some cases, the cracks occur as single, discrete surfaces, but in general, they occupy a zone a few grains wide. Crack segments wander and

anastomose, isolating long rectangular slabs a few grain widths wide and tens of grain diameters long. No visible evidence for sliding along these surfaces can be discerned, and it is thus concluded that they formed as mode I extension cracks. Individual grains can often be matched across the crack walls, a fact which lends further support to that hypothesis. Plate 4.1C illustrates the common distribution of these cracks within a section, as viewed in transmitted light; black regions are holes in the thin section, which presumably form when cracked zones drop out during section preparation. Plate 4.1E presents a more detailed view of the typical geometry, and a similar view in reflected light is shown in plate 4.1D.

Because crack densities in samples exhibiting only transgranular cracks are generally quite low, one is left wondering whether these pebbles have actually "failed" in the sense of experiencing severe stress drops. They may well have formed through stress corrosion cracking at differential stresses too low to produce catastrophic failure. In microstructural studies of pre-failure behavior (Sangha et.al., 1974; Scholz, 1968; Hadizadeh and Rutter, 1982), the formation of dense arrays of microcracks prior to a point representing the peak of the stress-strain curve has been well-documented. No evidence of similar microcrack formation is seen in these pebbles, though they may have formed and subsequently healed during burial. Cathodoluminescence studies are needed to test that hypothesis.

4.2.2.2 Patchwork Cracking

The first visible signs of more distributed cracking within samples is the development of a blocky, "patchwork" texture similar to that described by Hadizadeh and Rutter (1983) in association with rocks subjected to folding in the Italian Apennines. In pebbles deformed in this manner, cracking is still transgranular in nature, but the density of cracking is significantly higher (by a factor of 2 or 3) and more heterogeneous on the scale of a single thin section. A preferred orientation of cracks exists, but

the distribution tends towards bimodality. That bimodality accounts for the blockiness of the texture, since crack intersections isolate intact polycrystalline fragments (Plates 4.2A,B). Three differences distinguish the style of deformation mechanistically.

(1) Some deformation is distributed away from discrete crack surfaces; this occurs in the form of cracking at grain boundaries, accompanied by isolated fragmentation at the edges of grains. This evidence seems to suggest a loosening of the microstructure not seen in rocks which exhibit long, sub-parallel transgranular cracks.

(2) Grain size reductions occur in isolated zones, as in plate 4.2C. This generally occurs in areas where the fracture spacing is reduced to a few grain sizes in width. It may reflect the onset of frictional sliding, possibly along surfaces that opened in extension mode and subsequently served as easy slip surfaces after intrapebble rotation. These zones are always restricted to widths of a few grain diameters (i.e. <1mm.) and are distributed throughout the sample.

(3) Along some transgranular cracks, grains have been split in two, and are seen to have been offset by a few hundred microns (see Plate 4.2D). No granulation is seen along the surfaces when viewed in transmitted light, and traces appear considerably less wavy than those already described. It is thought that these may have originated as mode II (sliding mode) cracks, with initial displacements parallel to the propagation direction. While it is impossible to prove that assumption, the very possibility that mode II cracks with lengths of more than a few grain diameters exist is highly surprising, since fracture mechanics considerations show that considerably more energy is required to form mode II cracks at the expense of the mode I type.

4.2.2.3 Faulting, Deformation Banding, and Distributed Cataclasis

In samples which exhibit the most extensive cataclastic damage, a marked disintegration of the initial microstructure occurs. In a loose sense, deformation remains

PLATE 4.2 - Optical micrographs from "patchwork" cracked samples.

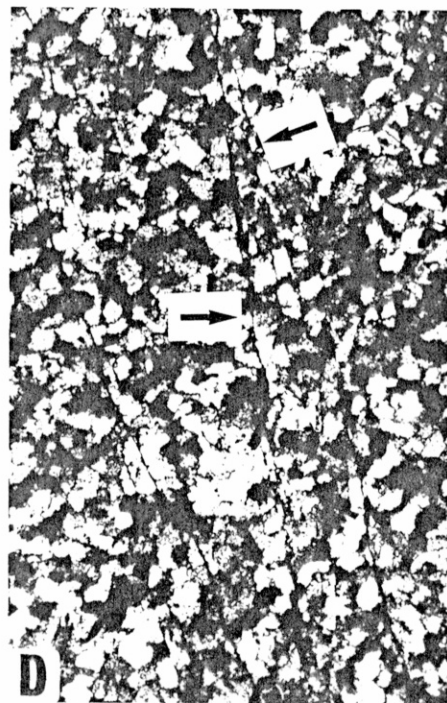
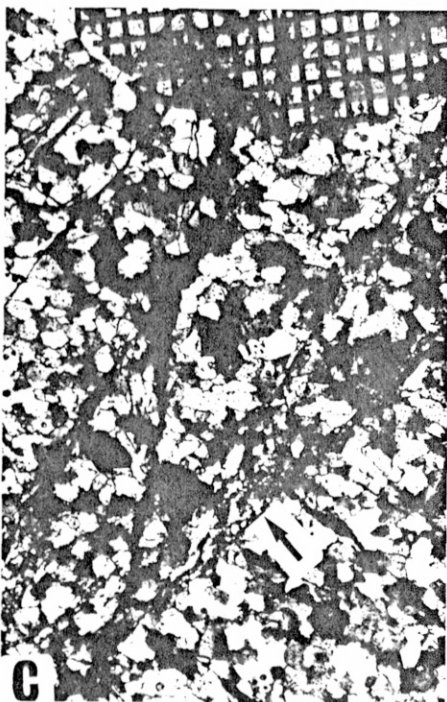
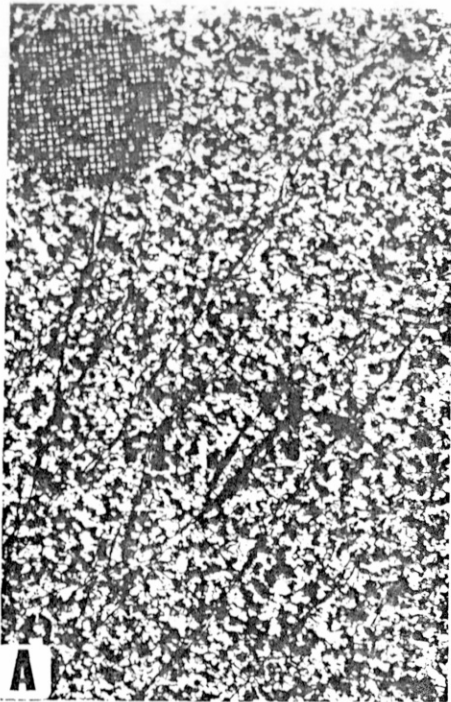
A. General patchwork appearance, as viewed in transmitted light. Black zones are holes in thin section.

B. Patchwork zone at higher magnification. Texture is similar to (A), but some granulation along cracks is observed.

C. Close-up view of grain size reduction along crack (arrow) at patchwork intersection.

D. Appearance of cracks inferred to have propagated in shear mode II. Some offset of quartz grains on either side of crack planes (arrows) is commonly observed.

PLATE 4.2



predominantly localized along faulted surfaces, but in segments of individual thin sections, that faulting occurs in networks dense enough to spread the cataclastic damage homogeneously over blocks with areas of a few square millimeters. In describing these samples a specification of scale is fundamentally important, since a hierarchy of dimensions exists:

(1) On the scale of a thin section (35mm x 25mm), cracks and faults are rather uniformly distributed. The overall structure is characterized by a mosaic of intact polycrystalline blocks of varying dimensions (from a few to ~30sq. mm. area) surrounded by semi-discrete and often conjugate surfaces along which high density microcracking and grain size reduction is seen. House and Gray (1982) observed similar structures in cataclastically deformed rocks along the Saltville thrust in the Appalachian foreland (Eastern U.S.A.), and applied the term "button structures".

(2) On the scale of a few mm., dense cracking with marked volume increase produces zones of widespread fragmentation. Smaller polycrystalline blocks comprising <50 original grains float in a dominantly fine grained matrix which, in detailed SEM study, is seen to have undergone pervasive diagenetic alteration.

(3) The zones of matrix material can occur in closely spaced (<1mm apart) subparallel networks (akin to the deformation bands described by Aydin (1977) or the cataclasite zones of House and Gray (1982), or in polygonal zones of < a few sq.cm. dimensions. The latter geometry occurs when entire polycrystalline blocks rotate to create dilatant spaces; fluid infiltration enhances retrogression of the clay matrix and corrodes the fragments of quartz.

Although this fine-grained microstructure appears

similar to the cataclastic flow textures described by Hadizadeh (1980), certain differences are noted which reflect differences between laboratory and natural conditions. The diagenetic alteration and crack healing seen in the pebble samples complicate micromechanical interpretations by effectively masking microcrack evidence which is easily obtainable from freshly deformed laboratory specimens. In that respect, the textures observed in the pebbles more closely resemble those seen in natural quartz fault gouges, as reported by Engelder (1974). Quartz fragments with diameters ranging from tens to a few hundred microns are surrounded by very fine grained ($<10\mu\text{m}$) phyllosilicate minerals. Both infiltrative and diffusional mass transfer mechanisms are locally important, and these have acted to produce a microstructure that probably only vaguely resembles that which existed at the time of deformation.

It is suggested that this final microstructural type may serve as a natural example of cataclastic flow on the millimeter scale. In a later section, mechanisms which might be invoked to explain the transition from discrete faulting to more distributed cataclasis will be discussed. Here it should simply be noted that none of the samples studied exhibit evidence for deformation which is in any way comparable to the intense grain-scale cataclasis observed by Hadizadeh and Rutter (1983) in rocks thought to have deformed via experimentally-induced cataclastic flow. In those experiments they noted the formation of networks of conjugate shear faults, often containing ultracataclasite (rock with $>90\%$ matrix (Sibson, 1977)), spaced by one grain diameter. These isolated intact grain cores contained extension microcracks, and were only observed at extremely high confining pressures. One might speculate that with increasing permanent strain accompanied by strain hardening effects, these zones could be produced in deformed pebbles, perhaps through the progressive breakdown of polycrystalline blocks. Alternatively, the absence of grain scale cataclasis in the deformed pebbles might be explained by a host of mechanical parameters wholly unrelated to the total amount of inelastic strain in a specimen. The various theories

might be further explored by sampling pebbles which show visible signs of more intense deformation.

4.3 MORPHOLOGICAL CRACK CHARACTERISTICS

In the previous section, 3 separate classes of failure behavior have been documented, according to the extent of visible damage observed in individual thin sections. The classification is primarily based upon differences in textural appearance as they are seen at relatively low magnifications in the optical microscope. These textural variations may reflect differences in the magnitude of applied differential stress, pore fluid pressures, or lateral confining pressures from pebble to pebble, due to changing packing geometries and stress distribution in the pebble aggregate. Alternatively, they may represent changes in failure behavior which result purely from differences in initial microstructural parameters, under a set of fairly uniform loading conditions. In this section, the crack behavior within individual pebbles is considered in greater detail, in order to elucidate micromechanisms associated with failure. On the basis of these descriptions, it may then be possible to better constrain the conditions under which a given type of brittle response is to be expected.

4.3.1 Grain Boundary Assisted Transgranular Cracking

In the previous section, it was noted that long transgranular cracks constitute the only signs of visible deformation in some pebbles. In large areas away from these surfaces, the initial rock microstructure remains firmly intact, as was shown in plate 4.1B; grain boundaries are distinguished by trails of small, equant microcavities, which result from incomplete suturing of the secondary quartz overgrowths. The onset of cracking is generally marked by the propagation of throughgoing cracks which link individual microcavities to form rather irregularly shaped

grain boundary cracks, as shown in plate 4.3A. These cracks often tend to completely surround grains, and may be accompanied by isolated intragranular extension microcracks which break individual grains. Propagation of the longer transgranular cracks occurs through the coalescence of suitably oriented microcracks, as seen in plates 4.3B-D. The width of transgranular cracks varies, ranging from hairline cracks with widths of less than 1 μm . to much thicker zones which are often lined by a mineralizing cement.

The isolated nature of the "hairline" variety is demonstrated in plate 4.3B: one transgranular crack with a marked kink transects a set of otherwise intact grains. Plates 4.3C,D show successively wider crack segments, but each exhibits clear grain boundary control. Branching is a common feature, particularly near crack terminations, as shown in plate 4.3E. Zones of a few grain diameters in width are broken into slender columns, a common feature of failure in low porosity rocks (Wawersik and Brace, 1971; Evans and Wong, 1985). In general, it is not possible to ascertain the relationship between crack orientations and the principal stress direction; little appreciable slip occurs along their surfaces, but they may nonetheless have been induced by small amounts of frictional slip. Hadizadeh (1980) considers shear rupture along suitably oriented grain boundaries to have been the main mechanism of failure when it occurred after only small amounts of inelastic strain in Oughtbridge gannister.

The SEM micrographs of plate 4.4 (SEI images) illustrate the extent to which microcavities along grain boundaries control the path individual cracks follow during propagation. Plates 4.4A-C are views of the cracked quartz microstructure at successively higher magnifications in specimen OL2. In 4.4A, a branched crack segment runs across the photo, and despite the presence of numerous microflaws on either side of the crack segment, these portions of the rock remain intact. The overall crack structure is characterized by microcavities with length/width ratios of between 3:1 and 10:1 linked by much sharper and thinner "slits". Microflaw width variations are more readily apparent in plates 4.4B,C. In 4.4C, extremely narrow slits

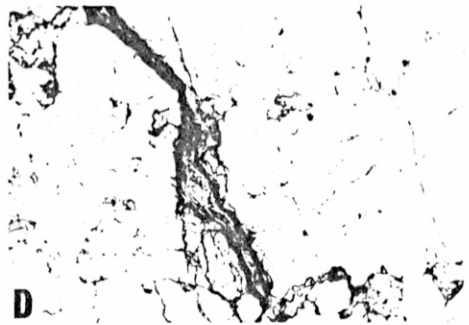
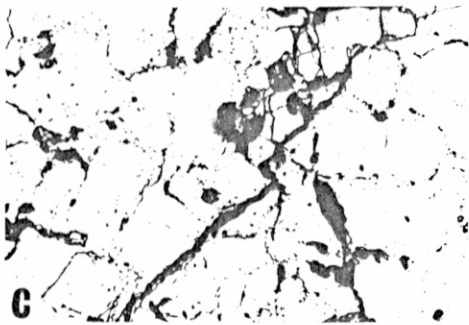
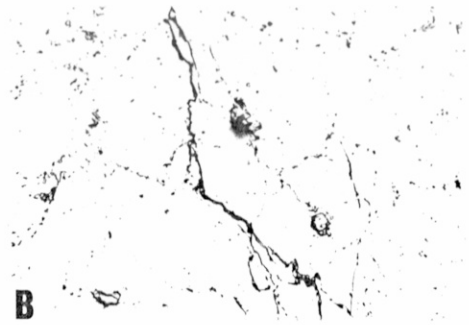
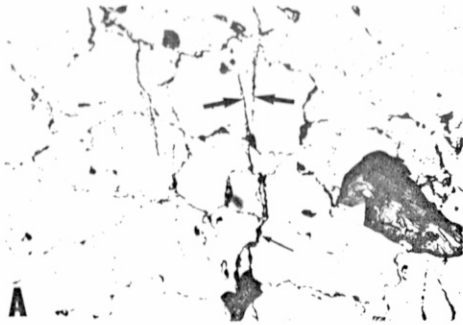
PLATE 4.3 - Reflected light micrographs illustrating morphologies of discrete cracks.

A. Throughgoing crack propagates both across (wide arrows) and around (thin arrow) grain boundaries. Outlines of grain boundaries are more visible than in Plate 4.1B, due to grain boundary cracking.

B-D. Sequence of progressively wider cracks which have propagated with characteristic "stepped" geometry.

E. Development of crack branching on the width scale of a few grain diameters. A series of subparallel cracks breaks the rock into a series of slender columns. Arrows indicate general crack trends.

PLATE 4.3



250um



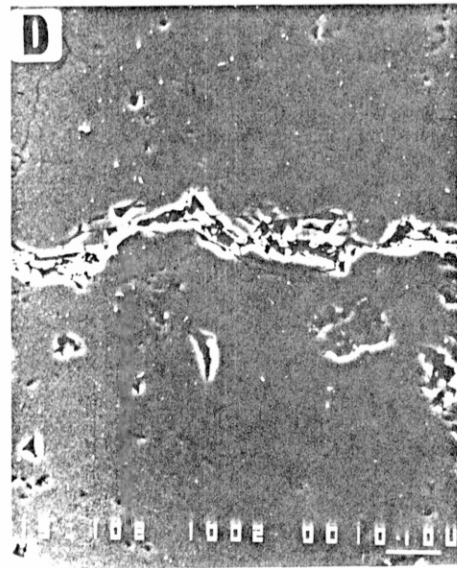
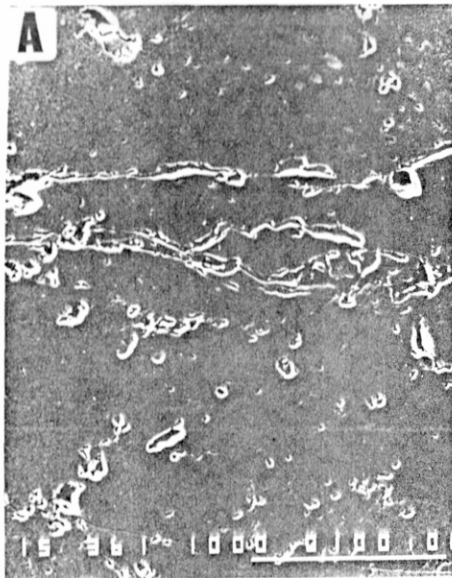
PLATE 4.4 - SEM (SEI mode) micrographs of discrete cracks. Machine-coded scale bars indicate scale in microns, and except where indicated, these represent the scale on all SEM micrographs.

A. Cracks link microcavities, which result from incomplete suturing of detrital grain boundaries by secondary quartz overgrowth cement. Most cracked pores have their long axes aligned parallel to the crack path.

B,C. Higher magnification views of crack-pore interactions. Large arrows in (C) point to hairline cracks linking circular pores, and small arrow points to a pore which has arrested crack propagation.

D. Microstructural appearance of wider crack segment. A small amount of sliding on the crack surface may be responsible for its slightly granulated texture.

PLATE 4.4



connect even the smallest cavities (wide arrows) away from the wider crack network. In addition, it is clear that non-suitably oriented microflaws can serve as effective barriers to crack propagation (small arrow). In all three photographs (4.4A-C), evidence for sliding is absent - any fragmentation of the quartz observed can be attributed to visible cracks. In contrast, plate 4.4D shows a distinctly non-planar microcrack array along which a small amount of milling appears to have occurred, leaving the crack margins with a slightly granulated appearance. Displacements have presumably been restricted to a few μm , since the grain boundary does not have a characteristically ruptured appearance.

4.3.2 Interactive Behavior in Patchwork Cracked Samples

As the crack density in a pebble increases, cracking along straight, sharp, widely spaced surfaces is suppressed. A higher density of grain-scale microcracks is generated, and throughgoing macrocracks propagate through the coalescence of these features in long (up to a few hundred grain diameter) bundles. Specimens take on a fragmented appearance but, except in very isolated places, no marked cataclastic grain size reduction is observed. The regularity of crack network geometries is influenced by the density of cracking developed. In zones where crack spacings are greater than a few grain diameters in width very regular patterns of crack interaction are seen, but as density increases microcracks proliferate in all orientations. These high density zones seem to be the natural equivalent of fault regions in rock specimens deformed under relatively low confining pressures (Dunn et.al., 1973; Hoagland et.al., 1973; Hadizadeh, 1980), although in the deformed pebbles, failure occurs along a whole series of densely spaced faults, rather than a single plane.

The common regular geometric pattern observed in rocks with the "patchwork texture" is an "en-echelon" network of cracks linked by shorter segments which form sets at high angles to the en-echelon trend. The pattern develops on many scales, and is not always controlled by the

orientation of grain boundaries, as in plate 4.5A. In plate 3.2A (ch. 3), a step-like crack pattern is developed on the scale of an entire thin section. Crack spacings are on the order of a millimeter, and numerous steps oriented parallel to the long axis of the micrograph link diagonally trending cracks. Plate 4.5B (SEI) shows a similar pattern. The en-echelon cracks (thin arrows) are less than 10um. and steps (arrowheads) a few microns long. The features are similar to both natural and experimental fracture configurations within larger zones, as reported by Sibson (1985) and Gamond (1983), and may represent displacement transfer features associated with small amounts of sliding on shear-oriented cracks.

Not all varieties of crack interaction produce the regular networks described in previous examples, particularly as microcrack density increases. Plates 4.5C,D are reflected light micrographs of zones with higher crack densities, and although two dominant trends can be delineated (arrowheads and thick arrows) in each example, the pattern is complicated by thorough grain-scale cracking. The rough bimodality of crack orientations provides convincing evidence that failure in some samples occurred through the coalescence of shear oriented macrocracks once dilatancy was achieved through the formation of extension microcracks. Spacing of fracture zones is heterogeneous, as illustrated in plate 4.6A; two high density zones containing throughgoing macrocracks are separated by a rectangularly-shaped area almost completely unaffected by deformation. These rectangular blocks are manifested on smaller scales, as in plate 4.6B. Here, the microstructure is broken into slender parallel columns between two larger epoxy-filled fractures, and subsidiary grain-scale microcracking of the type seen in plate 4.6A is absent. It thus seems likely that these cracks propagated in extension mode, and did not form via the coalescence of microcracks. The latter mechanism seems to have been responsible for macrocrack propagation in plate 4.6A.

A few authors (Tullis and Yund, 1977; Dunn et.al., 1973) have proposed that sliding movements within locally developed zones of high microcrack density precede

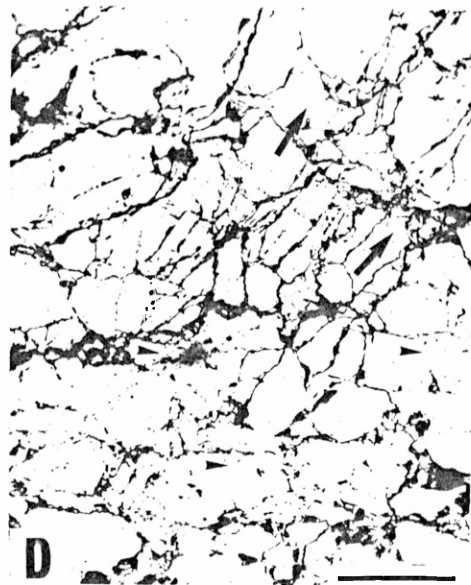
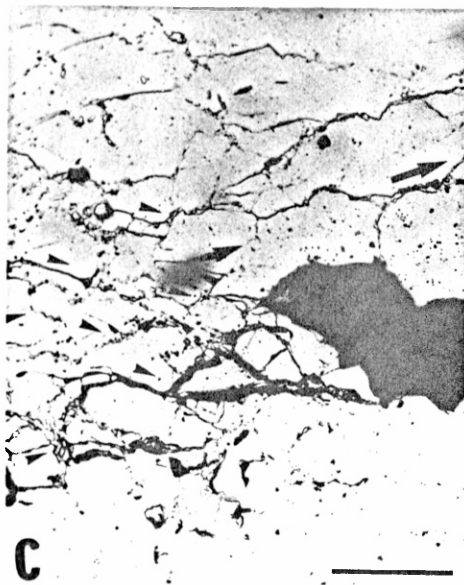
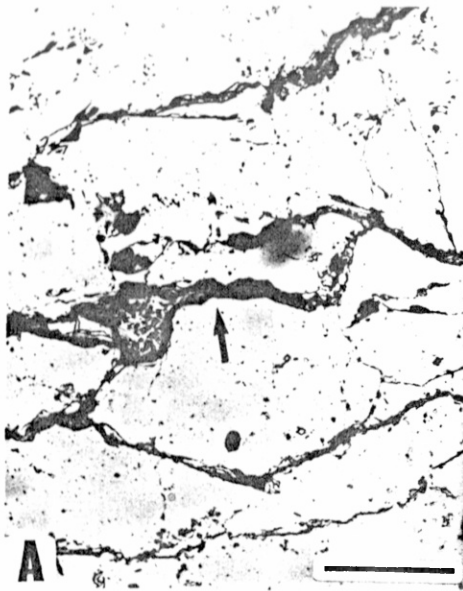
PLATE 4.5 - Crack Interactions. Scale bars in A,C,D =200um.

A. Stepped cracking in coarse grained sample (ABI). Note the small number of visible microcracks. Arrow points to grain boundary.

B. SEI micrograph showing stepped cracking on smaller scale. White arrows indicate mean fracture trend, and arrowheads show orientations of linked segments.

C,D. Reflected light micrographs from zones exhibiting higher microcrack density. Arrowheads delineate grain-scale microcracks, and larger arrows show mean trends of macrocracks.

PLATE 4.5



the more widespread development of concentrated deformation leading to the production of fault gouge. Conclusive proof of that hypothesis is extremely difficult to obtain, because even minor rotations of broken fragments causes rearrangement of constituent parts and collapse of the original microstructure. It seems likely that the microstructure must be relatively "loose" before rearrangements of particles occurs. Those rotations must involve an overall volume increase (positive dilation) in rocks of initially low porosity, and it is thus instructive to look for evidence for dilation in the form of increased fluid access.

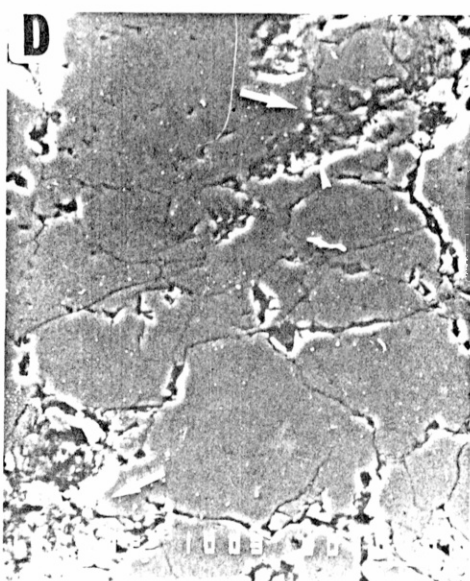
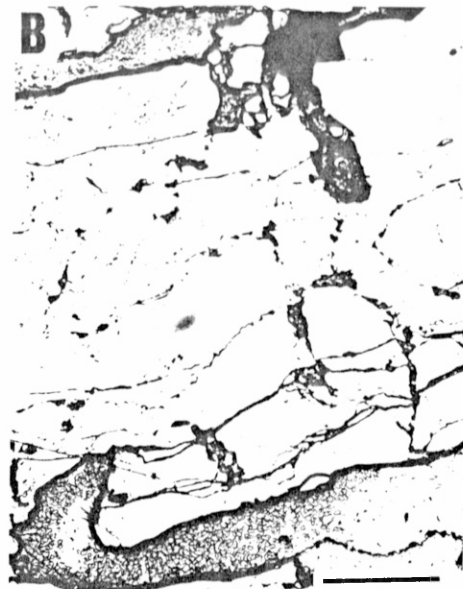
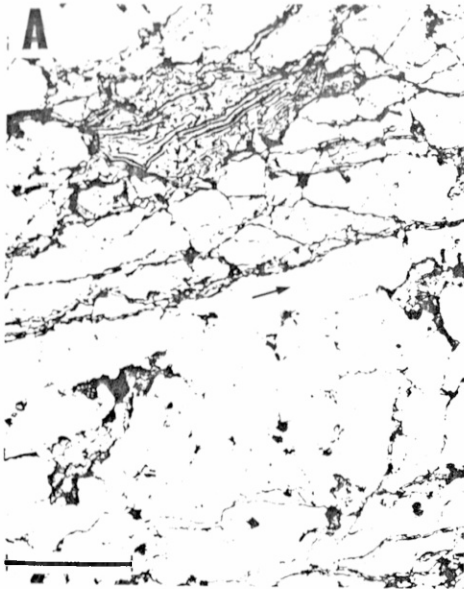
Fortunately, that evidence is fairly easy to obtain with the SEM, since clear resolution at high magnification enables detailed examination of both crack surfaces and pore spaces, along which fluids might be expected to move. Plate 4.6C (SEI mode) shows a region transected by two transgranular cracks, and indicates the role diagenetic reactions play in creating the appearance of grain size reductions along crack segments. The zone of visible damage spreads from the crack surfaces themselves into the intact rock, but the granulated texture one sees in transmitted light here appears to result less from mechanical grinding than from chemical degradation of quartz in contact with phyllosilicate minerals which fill pore spaces. Between the two crack segments, the microstructural appearance of quartz is similar to that seen in the SEM micrographs of plate 4.4; cracking remains discrete, and segments connect initial microcavities. Immediately adjacent to the zone, however, a great deal of etching and pitting is observable. The topographic effects are relicts of the preparation procedure, since quartz is more resistant to mechanical polishing than are the pore-filling minerals. From the distribution of etched zones, it seems likely that enhanced permeability in the immediate vicinity of wide cracks enabled increased fluid access, which promoted diagenetic reactions leading to the chemical breakdown of quartz (by a dissolution mechanism to be discussed later). Those same fluids did not penetrate very deeply into the intra-crack fragments of polycrystalline quartz, and similar

PLATE 4.6.

A,B. Reflected light micrographs illustrating different forms of macrocrack propagation. In (A), arrow marks mean macrocrack trend, and separates zone of high microcrack density from the nearly uncracked zone below. In (B), columnar cracking occurs between wider epoxy-filled fractures. Microcrack density is low, and cracks are thought to have opened in extensional mode. Scale bars = 200um.

C,D. SEI micrographs illustrating textures commonly developed in specimens whose grain boundaries are lined with small amounts of argillaceous cement. Arrows point to sutured boundaries of quartz grains, which attest to pressure solution processes. Quartz is easily distinguished from clay minerals, due to its greater resistance to mechanical polishing. Machine-coded scale bars.

PLATE 4.6



degradation in that zone was prevented. Plate 4.6D shows a higher magnification view of the same phenomena. Sutured boundaries between the resistant quartz and pitted clay minerals attest to pressure solution of quartz, and the area of quartz dissolution appears to be spreading into the heavily microcracked zone between the two large pores.

4.3.3 Microstructural Characteristics of Cataclasite Zones

The most advanced stage of deformation within the group of pebbles studied is marked by the presence of semi-discrete zones of cataclasites, with maximum dimensions of one to a few millimeters in thickness. These consist of highly fractured quartz fragments and phyllosilicate minerals. The zones appear to have geometric configurations similar to a range of naturally produced cataclastic fault rocks, variably referred to as deformation bands (Aydin, 1977), protobreccias (Blenkinsop and Rutter, 1985), quartz fault gouge (Engelder, 1974), and cataclasite zones (House and Gray, 1982). The final term is preferred for the purpose of this study, since any true bands which develop are restricted to lengths of a few millimeters, and the zones are not localized along macroscopic faults of wide lateral extent.

It is believed that the cataclasite zones are generated due to frictional sliding along shear fractures or faults, but displacements along these surfaces must have been restricted to less than a centimeter, since the pebbles in which they occur show no visible signs of shape distortion. A detailed microstructural description of the textural characteristics within the zones is presented, in an attempt to elucidate factors which may be important in their generation. Since it seems likely that they represent an early stage in an evolutionary sequence leading to the formation of more widely distributed fault gouge, a thorough understanding of their characteristics may lead to more accurate constraints on certain kinematic aspects of fault gouge genesis.

4.3.3.1 General Description

It has been noted that some grain size reduction occurs immediately adjacent to long transgranular cracks in samples which have developed a "patchwork" texture. In samples containing more distributed zones of grain size reduction, discrete transgranular cracking is less common, but still present. The overall microstructure is characterized by millimeter scale polycrystalline blocks of quartz grains dissected by roughly linear but irregular cataclasite zones with average thicknesses of several hundred microns (plate 4.7A,C). In detail (plate 4.7B), these zones contain strands of quartz grains which in some cases appear to have been ripped from the adjacent intact walls and become incorporated into the finer grained matrix, as in plates 4.7D,E. Commonly, the outlines of what appear to have been cataclasite zones are preserved, but a calcite cement fills the banded void, as in plate 4.7F. In this photograph, both cataclasite (thin arrow) and cement (thick arrow) fill a vein, and small fragments of quartz are surrounded by the cement at the boundary between cement and cataclasite. This relationship demonstrates the fact that widespread fluid infiltration occurred after the formation of the cataclasite zone.

Because samples in which cataclasite zones develop display markedly more granulated surfaces than all other specimens studied, it is appealing to consider them as more strongly deformed counterparts of pebbles which have cracked along discrete surfaces. Numerous experimental studies have shown that the transition from localized faulting to distributed cataclasis occurs with an increase in effective confining pressure, as the enhanced normal stresses at crack interfaces inhibit frictional sliding and cause permanent strain to be accommodated by more widely distributed microcracking (see Handin et.al,1963; Byerlee,1968). Additionally, porosity is thought to play a major role, as discussed briefly in chapter 2. Aydin (1977) found that deformation bands form in high porosity (>20%) sands due to impingement microcracking which promotes pore collapse, a point which will be considered in the discussion at the end of this chapter. While both of these factors may influence

PLATE 4.7- Optical micrographs from cataclasite zones. Scale bars in C,D = 200um.

A. General cross-polarized appearance of cataclasite zones (arrows).

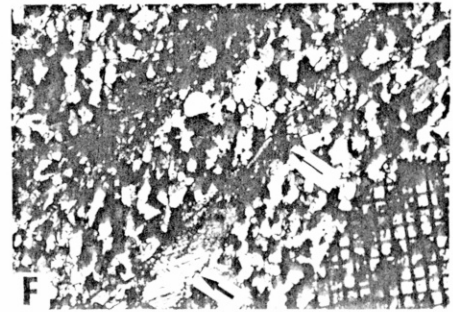
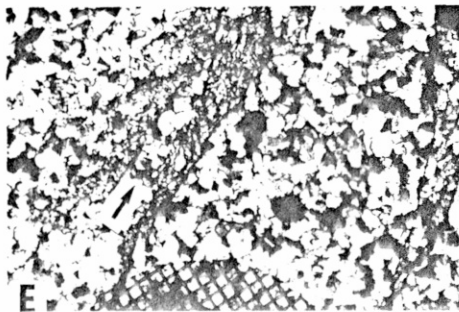
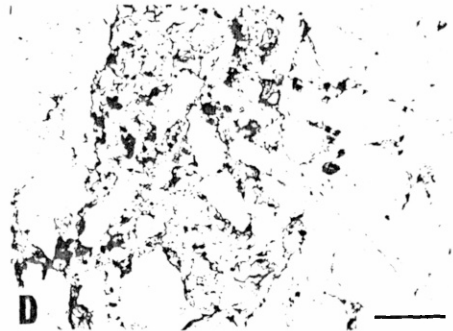
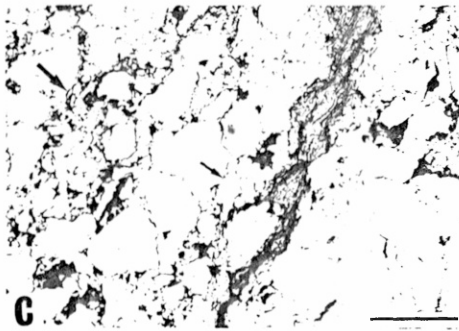
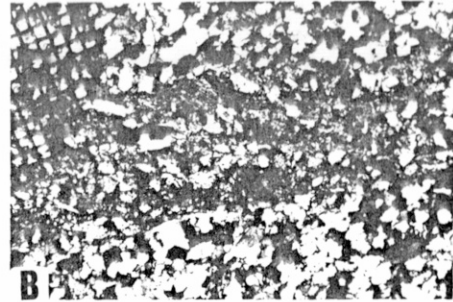
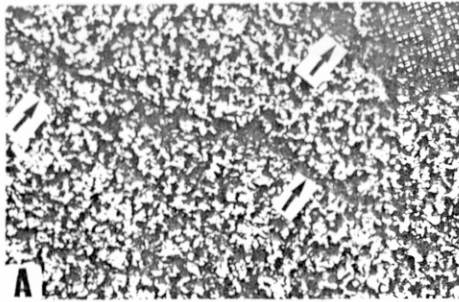
B. Detailed view of cataclasite zone. Coarse grained quartz fragments float in a matrix of finer-grained quartz and clay minerals.

C,D. Reflected light views of cataclasite zones. Arrows in (C) point to irregular zones exhibiting minor amounts of granulation and grain size reduction, which can be compared with the texture in a more banded area (D). Large quartz fragments in (D) appear to have been ripped from intact walls and rotated into the matrix.

E. Narrow strip of intact quartz (arrow) formed where wider cataclasite band branches into narrow segments.

F. Carbonate cement (wide arrow) replacing cataclasite band (thin arrow). Fine-grained fragments of cataclasite appear to be floating in the carbonate cement along the walls of the segment between arrows.

PLATE 4.7



the style of deformation which is seen in the deformed pebbles, neither explanation seems particularly satisfactory. Pebbles are certainly constrained in directions perpendicular to the compression direction by forces arising at point contacts, but it is difficult to envisage confining pressures of 500 to 1000 MPa arising from these lateral constraints. Experiments (Hadizadeh and Rutter, 1983) show that effective confining pressures of these magnitudes are required to produce widespread cataclastic flow in the laboratory. There is less evidence for the existence of very high initial porosities in any of the pebbles studied.

One significant difference is readily apparent between samples which crack cleanly and those which develop cataclasite zones, however, and evidence gathered with the SEM attests to its mechanical importance. Samples ABIII and OL1 contain far higher proportions of detrital phyllosilicates which line grain boundaries (often in substantial thicknesses), and authigenic clay minerals which fill interstitial pores. They also exhibit poorer original sorting and greater grain shape angularity, as well as average grain sizes of less than 100um. All of these factors distinguish them from the cleaner, coarser orthoquartzites which lack cataclasite zones. It is thought that the presence of micas and clays weakens the mechanical strength of stressed grain boundaries, due to competency and compressibility contrasts between different mineral phases. This will serve to facilitate both grain boundary and transgranular cracking at an early stage in the load history. Dilatancy due to cracking permits greatly enhanced access to fluids which promote diagenetic processes. In turn, these retrogressive reactions promote the breakdown of quartz by largely chemical means.

4.3.3.2 Undeformed Appearance

Because cracking is so widely distributed within specimens ABIII and OL1, it is difficult to find uncracked zones at magnifications within the range of the SEM. Evidence of diagenetic alteration is abundant. Plate 4.8A

illustrates a few salient features. The SEI image retains some backscattered contrast, and kaolinite (K) and illite (I) can be readily distinguished from quartz on the basis of both BSE contrast and morphology. White arrows point to unaltered pore-filling kaolinite, and black arrows indicate areas where an incomplete breakdown of kaolinite to illite has occurred. The clays are cracked, and it thus seems likely that they were inherited from the parent sandstone, rather than post-dating deformation. Similar textures are seen in plate 4.8C; microcracking in the large quartz grain (Q) develops, but has been insufficient to allow thorough alteration of kaolinite (K). Plate 4.8B is a higher magnification BSE image of predominantly incoherent authigenic illite (with a characteristic wispy texture) filling pore space. Also notable is the presence of both dolomitic (D) and calcite cement (C) which have been thoroughly cracked. Since the deposition of carbonate cements can generally be demonstrated to have accompanied cracking, this feature is indicative of the episodic and geologically contemporaneous nature of cracking and cementation events.

4.3.3.3 Structure of Cataclasite Zones

These undeformed characteristics can be compared with micrographs from within the cataclasite zones themselves, in which granulation of quartz grains becomes an important mechanical process. Plate 4.8D is a low magnification SEI view of a reasonably well banded zone. White arrows delineate the band boundaries, and topographic effects distinguish quartz fragments from the clay minerals. Areas outside of the band are substantially less altered than those within, and contain few microcracks. In the same photograph, the effects of grain fragmentation and rotation are unmistakable. The largest clast is approximately 200um. long, and unaltered fragments of sizes as small as a few microns are resolvable at this magnification. A few of the fragments contain intragranular cracks, but rather than radiating from impingements, these appear to be inherited from the original grain boundary microstructure. Most

PLATE 4.8.

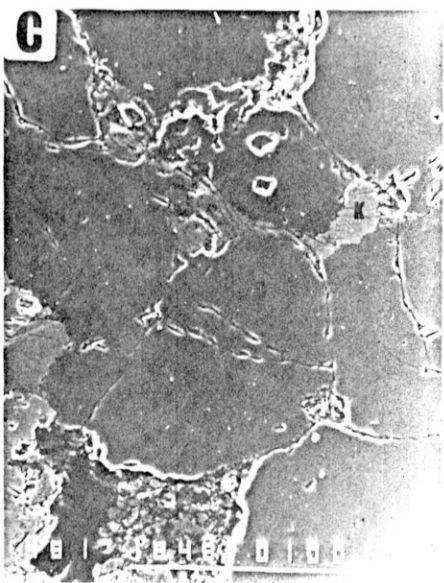
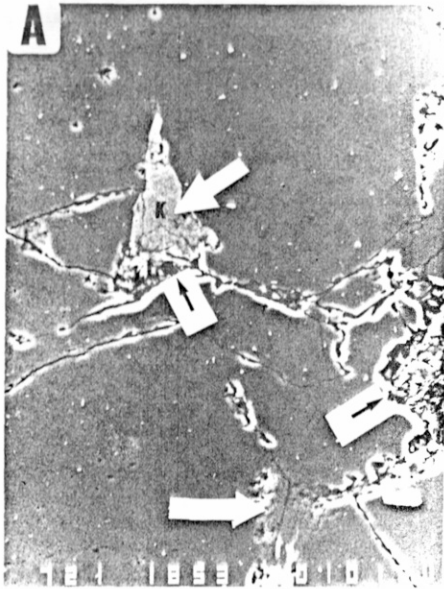
A,C. SEI micrographs showing common texture in relatively uncracked segments removed from cataclasite zones. Kaolinite (K) fills pores (white arrows), and is incompletely replaced by illite (I) along crack segments (black arrows) in (A). Kaolinite appears relatively unaltered in pores surrounding quartz grain in (C), though large-scale alteration is seen near scale bar.

B. BSE micrograph illustrating diagenetically-induced textures in zone of brecciation. Dolomite (D) and calcite (C) bearing cements are cracked and fragmented, and wispy illite grains (I) fill the dilatant space.

D. Low magnification SEI micrograph from cataclasite zone between white arrows. Contrast between quartz fragments and clay-rich matrix is readily apparent. Note the lack of alteration outside of the zone proper.

Machine-coded scale bars.

PLATE 4.8



fragments are completely surrounded by low relief matrix material, and the embayed appearance of the quartz boundaries provides evidence for dissolution processes.

A series of higher magnification SEI micrographs are presented in plate 4.9. In 4.9A-C, the largest fragments are smaller than 50um. in diameter, and wholly mechanical fragmentation along cracks occurs down to dimensions of a few microns. In 4.9D, grain sizes are all less than 10um in diameter, and the average grain size of visible fragments is between 1 and 2um. Detailed chemical analyses were not performed on the matrix material, but qualitative EDS analyses indicate the presence of illite, kaolinite, Fe- and Mg-rich chlorite, as well as carbonate material. Black areas are holes in the thin section, infilled with epoxy cement.

Especially within plates 4.9A,B, impingement fracturing is seen to occur between the quartz fragments. In all photographs, however, there is little indication that the applied load is being supported at grain contacts. The detailed geometry of the embayed margins is readily resolvable at these magnifications, and diagenetic alteration rims are sometimes preserved, as shown by the black arrows in plate 4.9C. The irregular nature of the cataclasite zone walls is significant in 4.9A,D; dense cracking appears to be freeing new fragments from the adjacent intact material, and widening of the cataclasite zones must undoubtedly occur by continued plucking of these fragments, due to the sorts of asperity-friction interaction envisaged by Engelder (1977). The point is further illustrated in plates 4.10A,B. In 4.10A, cracking is extremely limited and a combination of abrasion and dissolution processes appear to have been active in widening the fault gouge zone. In 4.10B, relatively low crack densities are observed along the zone boundaries, and deformation is concentrated within the interior of the cataclasite zone. The large fragment marked with a white arrow looks set to dislodge itself to relieve stress buildups at the neck of an irregularly shaped fracture. These conclusions generally coincide with those reached by Jackson and Dunn (1974) and Engelder et.al. (1975) from experimental studies of gouge generation in Coconino and

PLATE 4.9 -High-magnification SEI micrographs from within cataclasite zones.

A,B. Narrow zones of granulation, containing relatively low proportions of clay minerals. Large quartz fragments contain extension microcracks initiated at points of impingement between grains. Dissolution along grain boundaries is present, but not pervasive. Most fragments appear to result from mechanical granulation.

C. Wider, more severely altered cataclasite zone. The percentage of clay minerals is much higher than in (A) or (B), no extension microcracks are preserved within quartz fragments, and dissolution along quartz grain boundaries is pervasive (black arrows).

D. Well-banded cataclasite zone exhibiting extreme grain size reduction. Except within approximately 10um. of the zone margin, the adjacent walls are almost completely uncracked. Within the zone, the largest quartz fragment has a diameter of less than 10um.; most fragments have diameters of less than a few microns.

Machine-coded scale bars.

PLATE 4.9

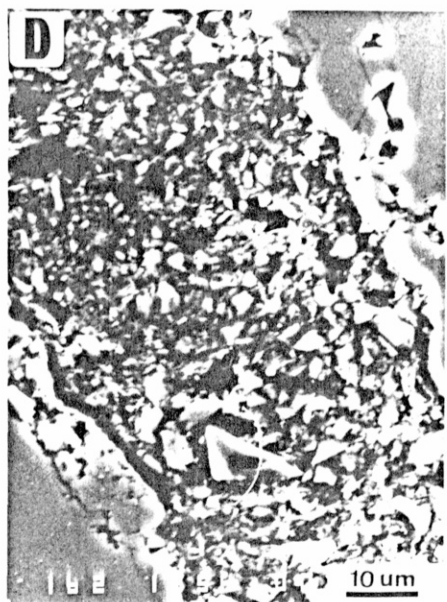
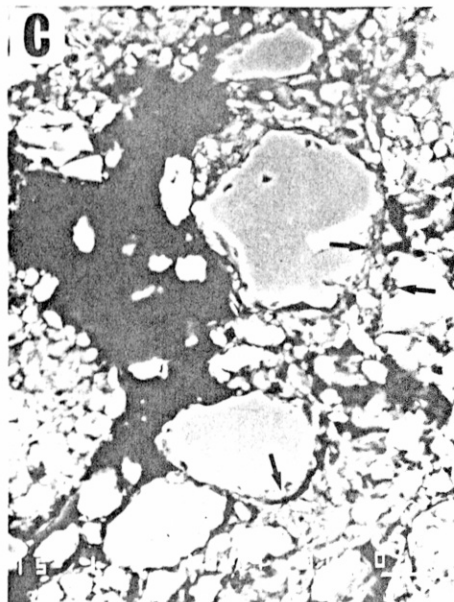
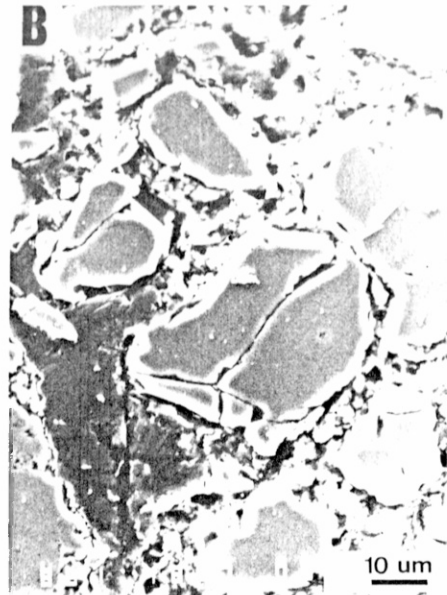
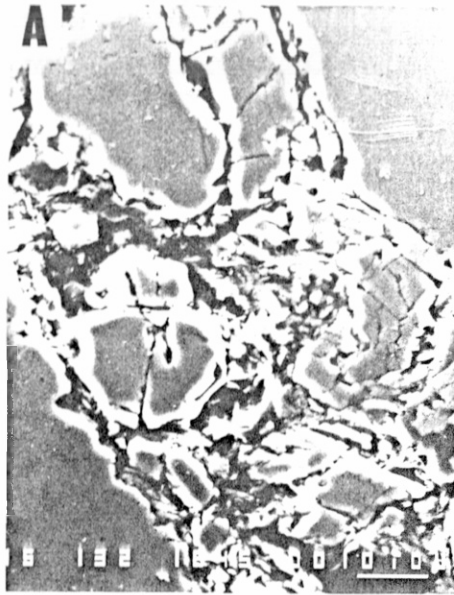


PLATE 4.10

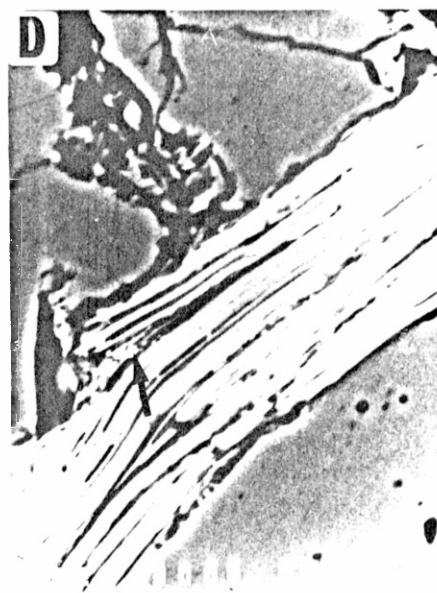
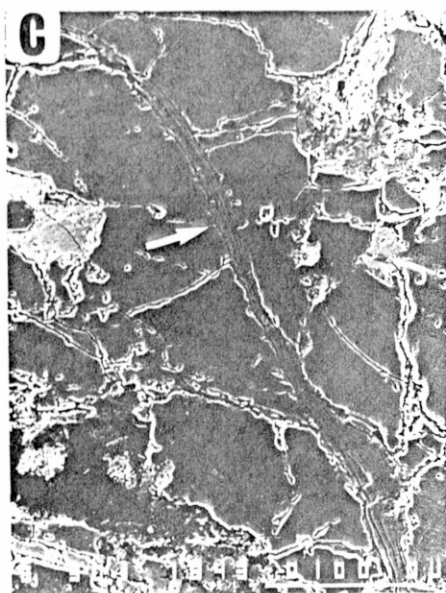
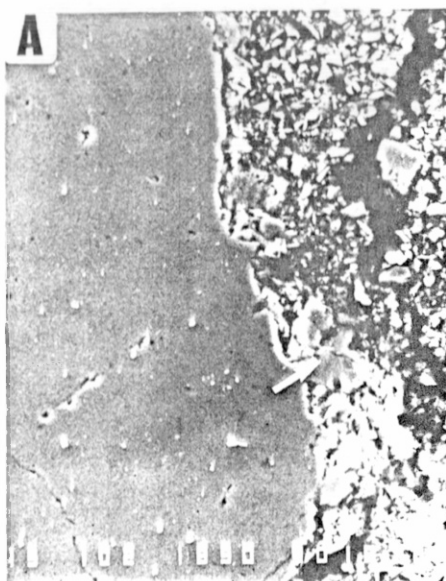
A,B. SEI micrographs illustrating the extremely localized nature of many cataclasite zones. Walls contain low densities of microcracks, and it is inferred that widening of the zones occurs by plucking of intact fragments during sliding. In (A), a small intact fragment of quartz (arrow) juts into the zone, and looks set to dislodge itself into the matrix. In (B), stress buildups at the neck of an irregularly -shaped fracture have induced microcracks which encircle still-intact fragments.

C. Low-magnification SEI image of detrital chlorite grain (arrow).

D. Higher magnification BSE image of chlorite grain in (C). The grain is cracked along its cleavage, backscattered contrast results from kaolinite intergrowths, and kinking of the grain occurs near the black arrow. At the tip of the arrow, illitic intergrowths appear to have wedged the grain open along its cleavage.

Machine-code scale bars.

PLATE 4.10



Tennessee sandstones, respectively. Further comparisons will be considered in the discussion to this section. It should finally be noted that sidewall fracturing of the sort reported by Hall (1983) from natural gouge-bearing fault zones is extremely limited.

4.3.3.4 Behavior of Detrital Phyllosilicates

It has been noted that the samples which contain abundant, distributed cataclasite zones also contain the greatest percentage of phyllosilicate minerals. The extent to which interstitial clays affect the mechanical behavior of these less quartz-rich samples has been briefly discussed, and will be considered further in the next section. Here, some of the more spectacular cementation and alteration effects seen in association with detrital phyllosilicate grains will be documented, as a means of illustrating the increased complexity of low-temperature deformation in sedimentary rocks with a significant non-quartz component. The potential importance of subcritical crack growth in rocks deformed in the presence of chemically-active pore fluids has been repeatedly emphasized in the preceding chapters of this thesis. Unfortunately, unequivocal microstructural evidence for stress corrosion cracking is extremely difficult to obtain (but see Kerrich et.al., 1977; White and White, 1981). This is particularly true in quartz-rich rocks where phase transformations are generally absent, and the results of this study do not prove the exception to the rule. Nonetheless, chemical transformations within the phyllosilicates attest to the influence of the chemical environment, and illustrate the interplay between deformation and diagenesis in rocks deformed at low temperatures and pressures.

Plates 4.10C,D and 4.11A,B illustrate textures commonly observed where detrital phyllosilicates are present in the initial microstructure. Plate 4.10C shows a low magnification SEI micrograph of a cracked region containing a

long detrital chlorite grain. It appears to be cracked along its cleavage, and a higher magnification BSE view of a similar grain (4.10D) illustrates two common features observed. Dark intergrowths of kaolinite are observed along the chlorite cleavage; these are thought to arise by mainly solid-state reactions. In addition, the grain is kinked, and some parting of the cleavage is seen along the kink band axis. Illitic intergrowths appear to fill the resultant void space (arrow). It is unclear whether that kinking is associated with pebble deformation or compaction; White et.al. (1984) have observed similar features in undeformed sandstones, and attribute the effects to solely compactive stresses.

A more strongly deformed chlorite grain (C) is seen in Plate 4.11A, wedged between two quartz grains entirely surrounded by clay minerals - note the bending of chlorite around a rutile crystal (T). The ends of the grain have a pulled-apart appearance, which presumably occurs due to grain rotations. Smaller phyllosilicate intergrowths are seen in plate 4.11B, and here the distinction between detrital and authigenic minerals is difficult to make. The large chlorite grain (C) is surrounded by both quartz (Q) and chlorite/hydromuscovite intergrowths, but smaller phyllosilicates, as well as Ti-rich minerals, appear to fill the interstices between cracked fragments.

4.3.3.5 Pore Filling Phases

For the purpose of comparison, plates 4.11C,D show the general appearance of secondary pore-filling phases whose authigenic origins are not in doubt. In 4.11C, an uncracked pore is filled with Fe-rich chlorite (C) and illite (I) intergrowths. Their lath-like structure indicates growth under non-deviatoric stress conditions. Chlorite (C) fills the pore-space between two quartz grains (Q); its "bookish" appearance distinguishes it from the detrital micas in the previous plate. Both examples serve to illustrate the marked differences in appearance of the pore-filling phases in uncracked regions. Mineral phase transformations again appear to be mainly solid-state

PLATE 4.11.

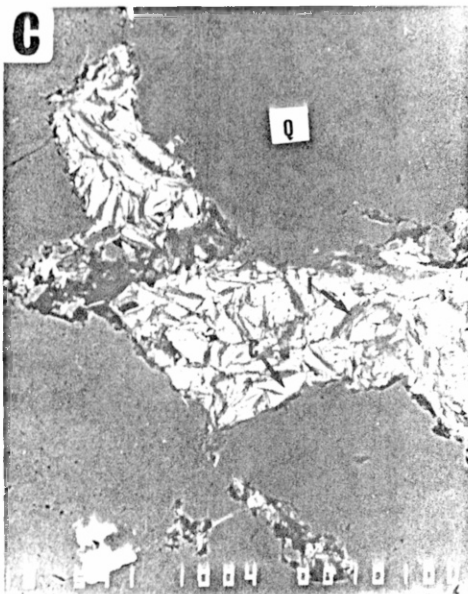
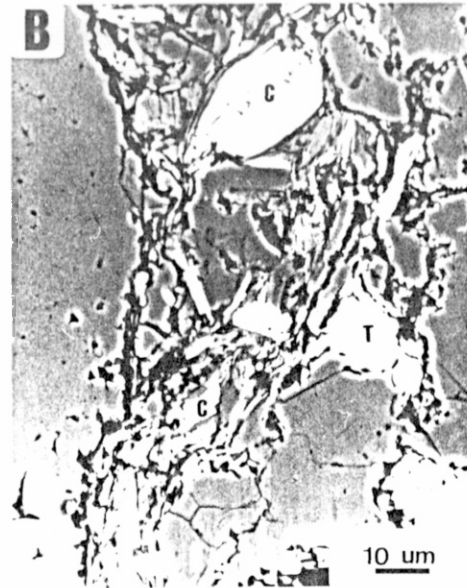
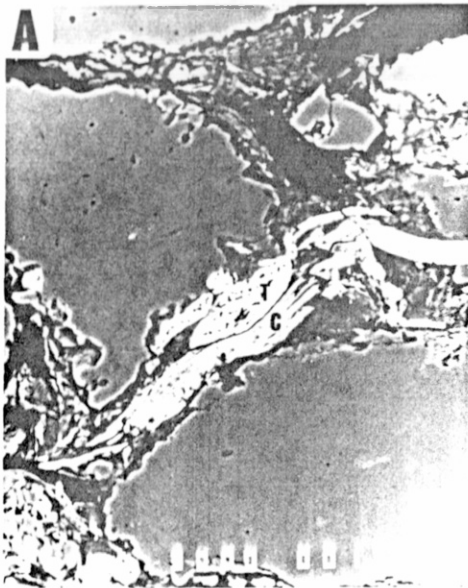
A. BSE image of detrital chlorite strand (C) pinned against a rutile grain (T) at pressure solution contact between quartz grains (Q).

B. BSE image showing complex interrelationships between detrital phyllosilicates and authigenic cement along a granulated grain boundary. A detrital chlorite grain (C) is in contact with a very irregular quartz fragment (Q). Small remnants of brecciated carbonate cement (C) and titanite (T) oxides fill the dilatant spaces.

C,D. Contrasting appearance of authigenic clay minerals filling pore spaces between quartz grains (Q) (BSE images). In (C), the pore is lined with intergrowths of chlorite (C) and illite (I). In (D) chlorite (C) fills the pore space, and develops with a characteristic "bookish" texture.

Machine-coded scale bars.

PLATE 4.11



processes, and are readily distinguished from those in which pore fluid plays a role in deformation.

4.4 DISCUSSION

Paterson (1978) has recently reviewed several aspects of brittle deformation with relevance to experimental rock deformation. Two areas in particular - friction and sliding phenomena and aspects of the brittle-ductile transition - have direct relevance to the results of this microstructural study. Given the existence of such a recent, comprehensive compilation, there seems little point in reviewing all relevant literature in these two focal areas. Instead, various aspects of crack propagation and cataclasite zone formation are considered in light of what I consider to be key studies. It is hoped that this will highlight some of the long-standing enigmas in the field of cataclastic rock deformation, and indicate ways in which the results of this study can be directly applied to them.

4.4.1 Propagation of Single Cracks

In the least deformed specimens (AB13, OL3) single macrocracks spaced by a few to tens of millimeters appear to have propagated in purely tensile mode across a specimen. Of the modes of failure seen in this study, it is the only one which might be predicted by Griffith-type theories of failure (see ch. 1). The formation of these features is undoubtedly favored when applied confining pressures are low, and when the initial rock microstructure contains only a limited number of microflaws. It was noted that this form of macrocracking can occur as single discrete surfaces, or exhibit a tendency to branch and wander into a few closely spaced crack segments. The mechanical basis for these varying morphologies has not been explored in detail in the geologic literature, but some progress has been made through studies of polycrystalline ceramics. Wu et.al. (1978) note three distinct styles of macrocrack propagation, which they

classify as (1) twisting, (2) wandering, and (3) branching. The first is considered to be important in non-crystalline materials, while the latter two are primarily observed in polycrystalline aggregates. Plates 4.1C,E attest to the importance of both in the quartzite conglomerate. The main differences between the two relate to the width of the affected zone. Wandering commonly occurs on width scales of <2 grains in extent, and was observed in all polycrystalline ceramics with grain sizes >30 μm . Branching occurred on a multi-grain width scale for fine grained ($<50\mu\text{m}$) samples, but was restricted to the few-grain scale for aggregates with coarser grain sizes (300-400 μm .). It was shown that branch separation increased with increasing grain size, and they thus concluded that the process results from a form of multiple twisting due to interaction with the grain structure.

Rice (1980) noted that branching only occurs for ratios of flaw size/grain size greater than 1:6. He suggested that the process may be initiated by grain boundary cracking, and proceed via the formation of stress-induced microcracks which form under the influence of the crack-tip stress field. Swanson (1984) supports that conclusion when it is applied to aggregates with a low pre-existing microcrack density, but proposed an alternative mechanism of microcracking via macrocrack coalescence where high densities of pre-existing microcracks are present. Grain boundary cracking appears to pre-dominate at slow crack velocities (Atkinson,1984), but with an increase in crack velocity approaching that for catastrophic crack propagation, transgranular cracking becomes more important.

4.4.2 Crack Interactions

Many experimentalists (e.g. Heard,1960;Wawersik and Brace,1971) have noted the tendency for extensional macrocrack propagation to be suppressed upon the imposition of confining pressures of as low as a few MPa; rock failure then proceeds along fractures that form from the coalescence of microcavities. Sangha et.al. (1974) note that anastomosing of microcracks and grain boundaries is a common

mechanism of fracture formation in rocks deformed under uniaxial compressive stresses. The importance of these mechanisms in the formation of the "patchwork" crack textures of some samples has been documented, and it has been further noted that as the density of cracks in a specimen increases, the propagation of individual cracks is influenced by the stress fields of nearest neighbors. Kranz (1979) studied the nature of crack-crack and crack-pore interactions in specimens of stressed Westerly granite, and characterized several general types of interaction on the basis of SEM observation. Figure 4.2 summarizes his attempts to classify a range of commonly observed morphologies. Similar intersections are observed in the quartzite pebbles of the Mieres conglomerate, but the ease with which grain boundary cracking occurs increases the geometric complexity of the resulting configurations, thus rendering them less amenable to mechanical interpretation. Nonetheless, certain regular networks are observed, and some attention will be paid to their mechanical significance.

4.4.2.1 En-echelon Cracking

In the brief introduction to fracture mechanics principles outlined in chapters 1 and 2, it was noted that propagating cracks tend to follow the local maximum principal stress trajectories, but that bending out of their plane occurs in order to maximize the strain energy release rate, and also to minimize shear stress effects. It has been further noted that grain boundary cracking constitutes the first sign of visible damage in fractured specimens of well-cemented quartzite, and that these microcracks effectively control the propagation of throughgoing macrocracks. These microstructural modifications undoubtedly influence the overall macrocrack geometry seen in deformed pebbles, but the single-pebble deviatoric stress fields are still seen to dominantly affect crack configurations.

One of the most common macrocrack geometries - the "en-echelon" configuration - appears to be controlled by the amount of overlap between closely spaced crack segments. The interaction between crack pairs has been studied

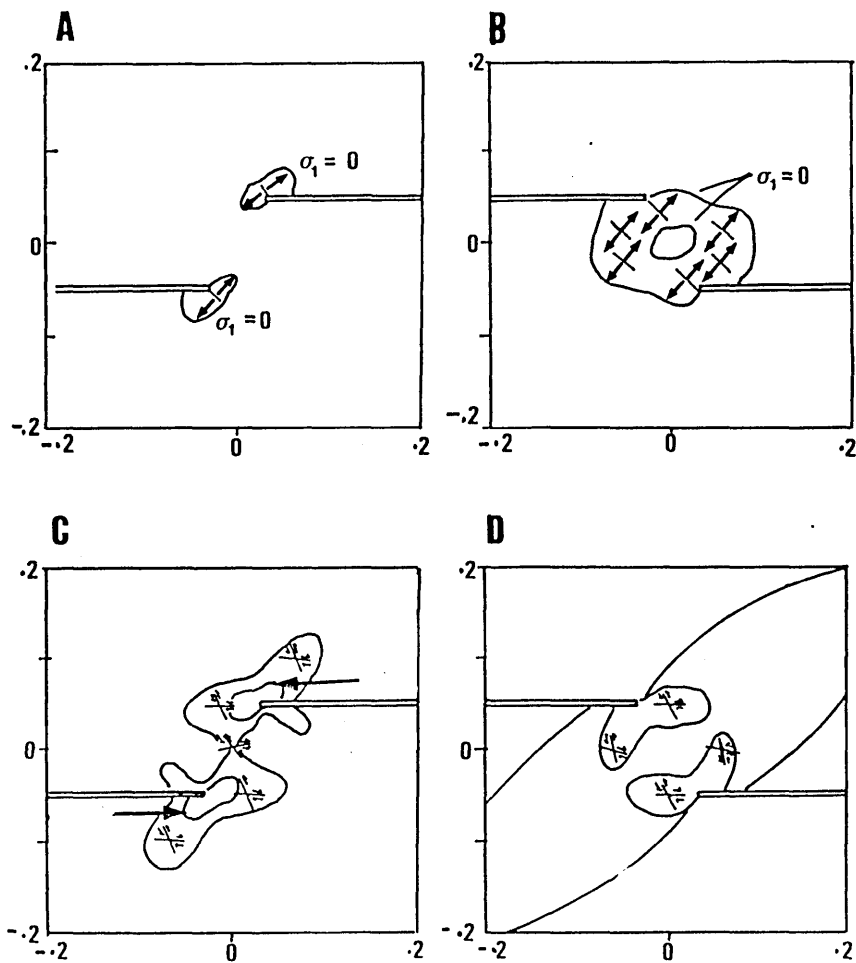
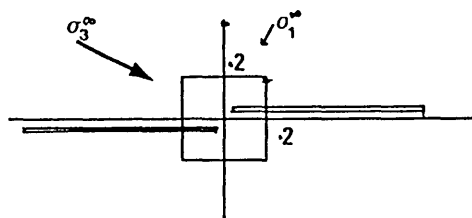
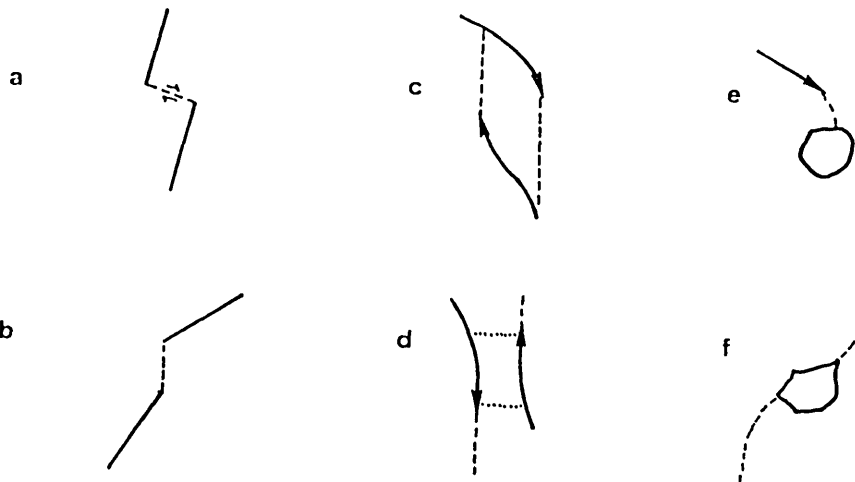
FIGURE 4.2 Schematic sketch of possible crack-crack and crack-pore interactions, after Kranz, 1979.

FIGURE 4.3. Secondary fracturing near en-echelon discontinuities. Contours of maximum tensile stress for left step (A) and right step (b). Contours enclose zones of tensile stress, and hence zone of likely tensile fracturing. Likely fracture geometries are drawn perpendicular to local maximum principal compressive stress. (C) and (D) show contours of likeliest locations of shear failure for left (C) and right (D) steps; potential shear fractures are located at 30 degrees to max. comp. stress. After Segall and Pollard, 1980.

EN ECHELON

EN PASSANT

CRACK-PORE



photoelastically by both Lange (1968) and Swain and Hagan (1978), and their results indicate that the tendency for cracks to link is controlled by the amount of overlap with respect to the maximum principal stress direction. A more rigorous analysis has been presented by Segall and Pollard (1980). They note that in detail, fault traces on all scales generally consist of numerous discrete segments arranged in en-echelon fashion, and arrive at a two-dimensional stress solution for non-intersecting cracks which takes into account the elastic interaction between segments. Their analysis focuses on shear cracks (along which movement is parallel to the existing discontinuity - mode II), and in it they consider two possible en-echelon configurations for either right-stepping or left-stepping senses of shear. The distinction is made by viewing the parallel network along trend; the direction of step is defined as the direction in which one must step to reach the next segment, as shown in figure 4.3. The most important conclusion from their analyses is the fact that, for right lateral shear, the amount of traction on left-stepping crack trends increases, whereas for right-stepping cracks, that normal traction decreases. As a result, sliding along left-steps is inhibited, the mean compressive stress between cracks decreases, and the formation of secondary fractures linking segments is suppressed. Conversely, sliding is facilitated along right-stepping cracks, the mean compressive stress between crack segments increases, and the formation of secondary fractures is favored. Figures 4.3A-D illustrate the possible secondary fracture configurations which might be expected for right-stepping and left-stepping discontinuities.

More recently, Sibson (1985) has questioned these findings, noting that "dilatational jogs" (the geometric equivalent of right-stepping discontinuities in right-lateral shear) have served as termination sites for recent earthquake ruptures. He argues that these features may act as kinetic barriers opposing rupture propagation; in order to transfer slip across the "jogs", extensional opening across the zones must be of the same order of magnitude as the amount of slip to be transferred. Unless

opening of the dilatant space occurred sufficiently slowly for fluid pressures to remain the same as those in the wall-rock, the opening will be opposed by a suctional force. The magnitude of that force appears to be substantial across large segments ($>.1m$). It may not, however, be high enough to offset the static stress effects which Segall and Pollard (1980) consider to promote slip for fractures of the sub-millimeter widths observed in these cracked pebbles.

4.4.3 Formation of Cataclasite Zones

The cataclasite zones observed in specimens ABIII and OL1 appear to have formed by markedly different processes than the deformation bands described by Aydin and Johnson (1983), despite their textural similarities to these features. Within porous sandstones, banding appears to be the result of matrix yielding and pore collapse (Aydin, 1977), followed by intragranular microcracking at grain impingements, which effects overall volume loss and strengthens the material by increasing the number of contact points per unit area (see Teufel and Logan, 1978). Given the low porosities seen in the quartzites, it seems likely that the formation of cataclasite zones produces local volume increases within cracked pebbles. Dilatancy accompanying deformation presumably results in increased permeability, and the enhanced fluid flow promotes both advective and diffusive mass transfer processes. The hydration of clay minerals may be important, but more detailed SEM work is needed on the clay minerals to better characterize the chemical effects.

There have been numerous recent attempts to explain the localization of deformation into concentrated zones in terms of a bifurcation in the macroscopic constitutive relations of homogeneous deformation in brittle materials (e.g. Cleary and Rudnicki, 1976; Rudnicki and Rice, 1975). Aydin and Johnson apply this approach to faulting in sandstone, and find that the theory can be used to adequately explain localization for a set of material properties consistent with field and laboratory observation. The pattern of multiple sets of closely spaced bands cannot

be explained by the same theories, but in an intuitive sense, this strain hardening effect has been addressed by Byerlee (1968). He noted the extreme pressure sensitivity of cataclastic mechanisms, and inferred that the transition from cataclastic faulting to cataclastic flow will occur at pressures at which the stress required to form new faults is equal to the stress required to cause continued sliding along the initial fault surface.

The widespread chemical processes documented in the microstructural descriptions of this chapter attest to the importance of fluids during deformation. Rutter et.al. (1985) describe the microstructures produced in long duration (up to 5 months) experiments on the creep of pre-faulted specimens of Tennessee sandstone at temperatures of 300 - 400 C, effective confining pressures of 150MPa, and pore pressures of 20MPa. Microstructural observations point to the importance of both frictional/cataclastic processes and water-assisted grain boundary diffusion creep. The initial microstructure is similar to that seen in specimens from the Mieres conglomerate which contain the highest percentages of interstitial clay, and the experimental fault-produced microstructures show certain similarities to those observed within the cataclasite zones of the conglomerates. In particular, quartz fragments within the Mieres rocks show a strong tendency to become rounded and embayed within zones with a high percentage of clays (plates 4.8D, 4.9B,C). The documented diagenetic reactions provide strong evidence for the circulation of pore waters in the natural examples, and the absence of similar reactions in uncracked portions of the rock suggests that diagenesis is facilitated by high fracture densities and associated positive dilatancy. The restriction of carbonate cement to specimens with cataclasite zones provides further evidence for crack-assisted hydrothermal fluid circulation.

The dissolution of quartz fragments within gouge and cataclasite zones has been the subject of much recent speculation. Rutter et.al. (1985) note that quartz-rich cement is produced during experimental faulting, with the silica derived from dissolution of quartz fragments and the recrystallization of original clays to a matrix of less

silicic composition. They point out, however, the apparent paradox of preferential dissolution of quartz in mica-rich regions with decreasing pore-fluid pH, together with silica saturation through the equilibrium of clay and the local pore fluid (a point also discussed by Dunning and Miller, 1985). The explanation offered by Rutter et.al. stems from the observation that quartz grains are generally loaded by relatively deformable phyllosilicates, as in plate 4.11A. That load occurs at an interfacial normal stress level commensurate with the mean stress level in the rock, which should raise the equilibrium activity of silica in the aqueous interstitial phase between particles. Assuming that the equilibrium activity of silica in the pore fluid is determined by pore fluid pressures, one might expect diffusive mass transfer of quartz from clay-rich to clay-poor areas, given the fact that pore fluid pressures are commonly less than mean rock pressures.

If these conditions act to "trigger" quartz dissolution, the continued corrosion of quartz might occur spontaneously, even at low levels of differential stress. Such an explanation may account for the size distribution of quartz fragments within the cataclasite zones, as seen in plates 4.9 and 4.10. The possibility that chemical dissolution and grain size reduction can occur in clay-rich fault zones places certain limitations on attempts to relate grain size distribution and gouge thickness to the amount of displacement along a faulted surface. In short-duration experiments on pre-cut sandstone specimens (e.g. Engelder, 1974; Engelder et.al., 1975; Teufel and Logan, 1978) the grain size distribution may indeed be related strictly to the amount of mechanical granulation a sample undergoes, which in turn will be a function of confining pressure, total displacement, and original grain size. In longer duration tests, and in naturally deformed rocks permeable to hydrothermally circulating fluids, the effects of chemical corrosion may produce cataclasite zones with very fine quartz grain sizes after only minor amounts of displacement. It seems that the presence of small but significant amounts of argillaceous material in a sandstone can profoundly affect the type of microstructure which will eventually

develop.

4.4.4 General Summary

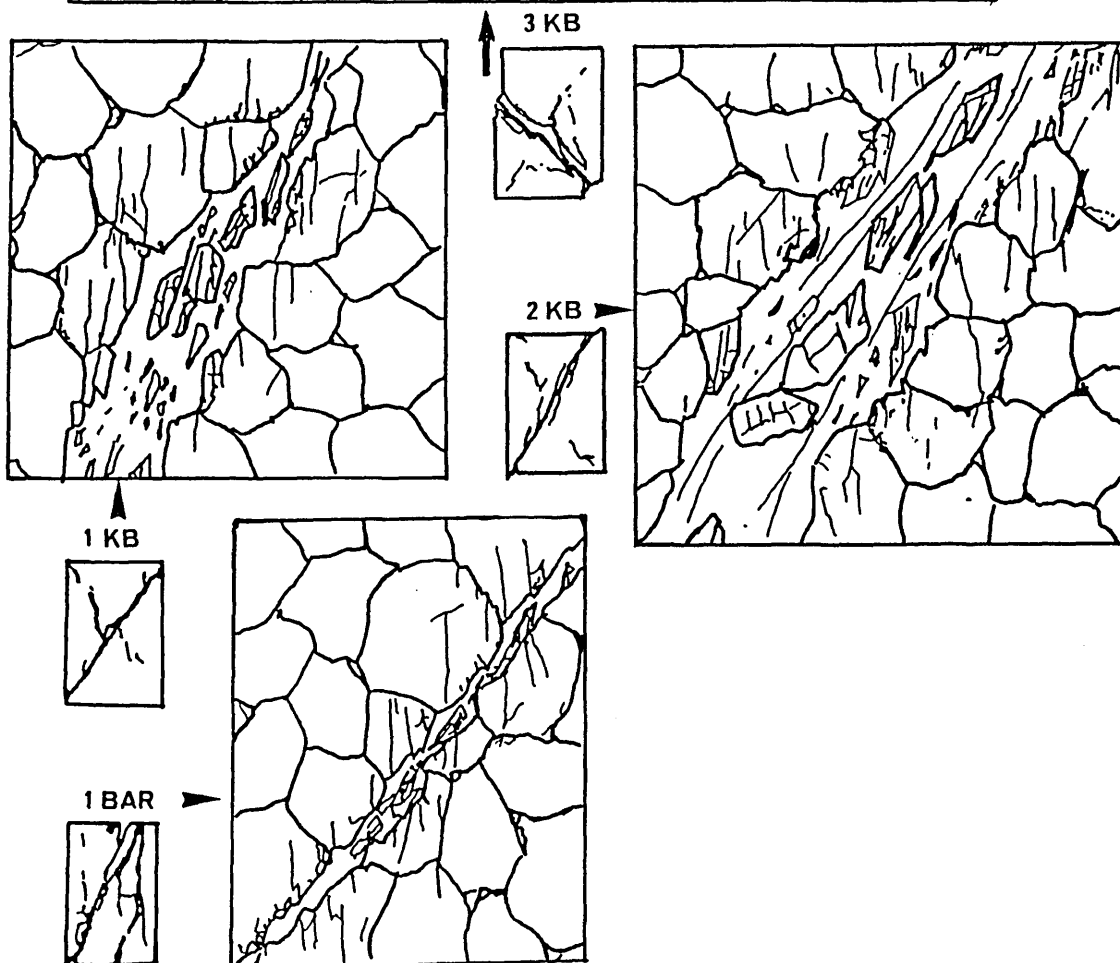
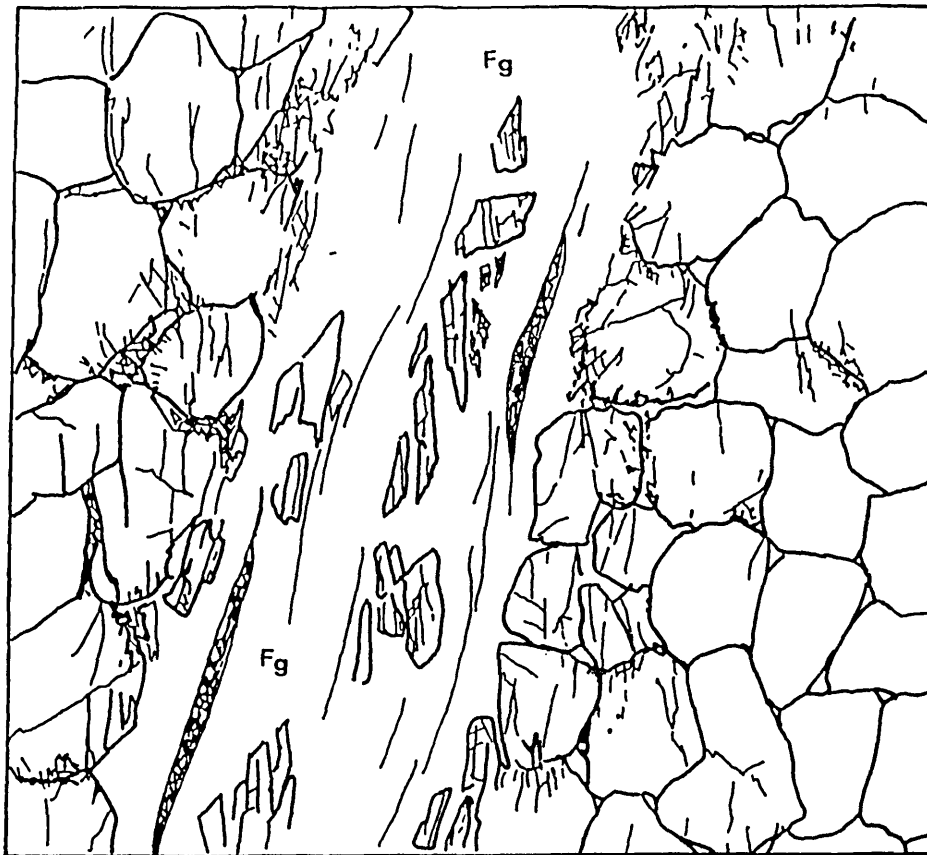
Table 4.1 summarizes the microstructural characteristics within the pebbles studied. While it fails to elucidate any striking correlations between original microstructural variables and deformation characteristics, a few findings are worth noting. Sample AB13, which is both the coarsest grained and purest of the quartzites studied, shows no signs of cataclasite formation. Cracking is discrete, and there is little evidence for chemical reaction. Samples ABIII and OL1, on the other end of the grain size spectrum, are generally the most poorly sorted and contain the highest percentage of interstitial argillaceous material. The presence of material heterogeneities at grain boundaries may facilitate their cracking, and allow for the influx of hydrothermal fluids which promote the corrosive reactions already discussed. It is difficult to assess porosity effects, since all microstructures are cemented with overgrowths of secondary mineral phases. It is also difficult to separate diagenetic effects on a pre-syn-post-kinematic time scale, and thus to determine their effect upon microcrack behavior. Some pore-fill material is clearly cracked, and it follows that some pore cementation preceeded pebble loading. It seems likely that quartz overgrowths of the type most completely developed in AB13 will retard the formation of microcracks to higher values of differential stress than the clay-rich overgrowths seen in ABIII and OL1.

Purely mechanical effects serve to complicate differences in crack behavior arising from differences in initial microstructure. Confining and pore fluid pressures, as well as total differential stress, might be expected to vary from pebble to pebble within the aggregate. Figure 4.4 illustrates the relationship between confining pressure and fault morphology, as determined from triaxial stress tests on Oughtbridge gannister (Hadizadeh, 1980). Increasing confining pressure produces a marked increase in the width of fracture surfaces, with all other variables held equal.

TABLE 4.1. Summary of microstructural features observed in samples studied, as seen using standard optical methods.

SAMPLE	GRAIN SIZE RANGE	GRAIN BOUNDARY COMPOSITION AND MORPHOLOGY	OTHER FEATURES	DEFORMATION CHARACTERISTICS
AB18	150-300 um.	quartz overgrowths clay rims equant to sutured shape	---	Transgranular cracking Cataclasis along cracked segments restricted to widths of less than one grain diameter.
OL2	100-200 um.	sutured to equant grain shape due to optically continuous silica cement clay rims rare		Limited cataclasis along t.g. cracks. Single irregular zone of cataclasis marked by widespread grain size reduction (30mm area). Shear cracks. Some plastic strain features.
ABIII	50-100 um.	pore-filling clays common most boundaries sutured "dirty qtz" overgrowths	detrital micas angular grains poor sorting	Abundant cataclasite zones, in semi-banded segments. Some cracking of cataclasite matrix. Few discrete cracks.
OL3	approx. 100um.	clay rims common qtz. overgrowths		Discrete cracking. Low crack density, with long cracks either sharp or containing small amounts of granulated material.
OL1	20-200um. mean = 50um.	pore-filling clays common dissolution of qtz. occurs at most boundaries, to give highly sutured shape	detrital micas poor sorting high angularity carbonate cement	Very little discrete cracking. All cracks show some grain size reduction associated with them. Cataclasite zones of varying widths common, with some grain size reduction resulting from chemical breakdown of quartz.
AB1	approx. 100 um.	mostly equant boundaries clean qtz. overgrowths.	well-sorted	Discrete or branched cracking with minor granulation. 1 cataclasite zone of 1-2 mm. width. Shear cracks.
ABI	100-150um.	clay rims common "dirty" qtz. overgrowths	well sorted	"Patchwork" cracking along discrete or slightly granulated cracks. No cataclasite zones. Shear cracks originate from contact marks at pebble edges.
AB13	approx. 200um.	clean qtz. overgrowths	---	Branched and sharp t.g. cracks, with little assoc. granulation. Low crack density; larger than average amounts of plastic strain
AB3	100-150 um.	qtz. overgrowths clay rims iron-oxide coats some boundaries	---	Branched, wandering t.g. cracks. No cataclasite.

FIGURE 4.4 Schematic representation of the relationship between effective confining pressure and fault morphology, as observed in triaxial stress tests on Oughtbridge gannister loaded to failure. Values of effective confining pressure are shown above hand sketches of failed specimens. Typical microfault morphologies observed after failure at each level of confining pressure are shown. After Hadizadeh, 1980.



Since some fine-grained specimens containing argillaceous intergrowths fail to form cataclasite zones in the studied pebbles, one must call upon lower effective confining pressures to explain the restriction of grain size reduction to widths of a few grain diameters in these specimens.

Differences in confining pressure from one pebble to the next might arise from differences in packing geometries within the pebble network. For pebbles loaded at both ends but only loosely supported on their sides, loading might result in uninhibited expansion in directions perpendicular to the applied load, due to elastic Poisson's ratio effects. If a pebble is very tightly packed by a host of surrounding pebbles (effectively "wedged" between its neighbors), that elastic expansion will be inhibited, and frictional sliding along discrete faults might give way to more distributed deformation. Pore fluid pressures should also be expected to play a mechanical role, but in naturally deformed rocks it will generally be impossible to infer their importance without a thorough quantification of overall stress levels.

Chapter 5

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

5.1 CONCLUSIONS

The conclusions of this study are presented in the order in which they appear in the text.

Mesoscopic Pebble Deformation

1. The Mieres conglomerate deformed via a process of impingement fracture at pebble contacts. The intra-pebble matrix was mechanically weak at the time of deformation, and the applied load was transmitted heterogeneously through the sedimentary succession, due to variations in packing geometry configurations and pebble shapes.

2. In detail, fractures are seen to develop as both mode I extension type and as shear faults along which millimeter-scale displacements occur. Fractures conforming to the classic Hertzian cone crack geometry are observed, but fracture mechanics calculations show that the force required to catastrophically propagate a single cone crack across an entire pebble is higher than tectonically-reasonable values by an order of magnitude. Calculations made using subcritical stress intensity factors provide stress values more in line with experimental rock deformation data. Fractures are seen to deviate from cone crack geometry in the interior of pebbles, and it is thus inferred that stress-field interference occurs due to the influence of neighboring point contacts, forcing the propagating fracture to choose a more energy-efficient opening direction.

Orientation Analysis

3. Three-dimensional orientation data indicate that

stresses were heterogeneous along strike of the conglomerate unit; inferred compression directions are not particularly well constrained, since it has been impossible to distinguish between shear faults and extension fractures on the basis of the distribution of the field data. Nonetheless, the fracture orientation distribution observed cannot be attributed solely to overburden stresses, since the vector representing the maximum principal stress direction shows consistent plunges of between 55 - 60 degrees. This is attributed to a tectonic "push" associated with thrust transport.

Attempts to correlate 2-dimensional crack data from oriented specimens with the 3-dimensional data gathered in the field yield equivocal results. The inferred compression direction from crack orientation statistics at Olloniego agrees well with the direction predicted on the basis of 3-dimensional results. At Ablana, the two different data sets predict markedly different compression directions.

4. Computer-aided pattern analysis is an extremely useful technique in the statistical study of linear data sets. With the aid of a hand-digitizing pad, large quantities of data can be generated quickly and accurately and subjected to rigorous statistical analysis. The results of this study indicate that large sample sizes are required to pick out mechanically significant crack orientations, and that task is greatly facilitated through the implementation of quantitative petrostructure techniques. In addition, orientation distributions gathered from planar cuts through cracked specimens generally mimic those obtained through more detailed thin section measurements. In a large regional study (e.g. along strike of a major upper-crustal fault zone), the acquisition of orientation data could conceivably be done from hand-specimen samples (which involve less elaborate preparation), with more detailed thin section measurements used to check the accuracy of the results.

Microstructures

5. Three distinct modes of failure were observed in

specimens prepared for microstructural study.

(i) Discrete extensional transgranular cracks, spaced by a few to tens of millimeters, develop in rocks with clean quartz overgrowths. Crack paths branch and wander, but visible damage is confined to a few grain widths. This type of cracking is thought to be common in rocks deformed in compression with little or no lateral confinement.

(ii) As observed crack densities increase, failure occurs along a series of interfering cracks of variable orientation, breaking the samples into a "patchwork" texture. Minor granulation along crack surfaces is observed, and "en-echelon" and "en-passant" crack arrays often develop. Grain boundary microcracking is more widely distributed, and retrogression of interstitial clay minerals, restricted to zones with high crack densities, attests to increased pore fluid activity due to crack-induced dilatancy. "Patchwork" cracking is thought to be favored by the imposition of small lateral confining pressures at pebble contact points whose normals are oriented at high angles to the compression direction. The importance of initial microstructure is an open question; the texture develops in samples with clean quartz overgrowths, as well as samples whose grain boundaries and pore spaces are lined with clay minerals.

(iii) The most pervasive deformation occurs in pebbles which contain the greatest percentage of interstitial phyllosilicate minerals. Widely distributed, gouge-filled cataclasite zones with widths ranging from a few grain diameters to one millimeter develop, and these are inferred to be faults along which maximum displacements of a few millimeters have occurred. Large quartz fragments ($>100\mu\text{m}$), presumably plucked from intact walls, are observed to float in a matrix of finer grained quartz and phyllosilicates. Carbonate cement is present, and in places it too is brecciated, a fact which suggests that episodic displacements occur within the zone. Detailed SEM observations indicate that grain size reduction of quartz

occurs through a combination of mechanical granulation along impingement cracks, and dissolution at stressed contacts with clay minerals. Diagenetic reactions are inferred to have facilitated sliding after crack-induced dilatancy increased pore-fluid permeability. Lateral confining pressures may have been higher than those imposed upon "patchwork" cracked samples, but it is extremely difficult to assess the relative roles of the various mechanical and chemical parameters which have been previously demonstrated to influence mode of failure transitions in cataclastically-deformed rocks.

5.2 SUGGESTIONS FOR FURTHER WORK

This thesis in effect reports the results of work arrested in-progress. Time constraints enabled only a single field visit, and a thorough study of the data collected has left some nagging questions unresolved. It seems appropriate to consider ways in which the conclusions presented above might be better constrained by further study.

1. The three dimensional fracture orientation data collected in the field and 2-dimensional crack data generated in the laboratory effectively exist as separate data sets. Pebble packing configurations have been shown to influence the geometry and density of fractures observed in the field, and differences in microstructural behavior have in part been attributed to inferred differences in local pebble-to-pebble load distribution. A thorough, annotated excavation of a volume of pebbles is needed to tie the two sets of data together. In this way, mesoscopic orientations can be recorded for each pebble, evidence for shear displacements can be assessed at the outcrop to distinguish between shear and extension fractures, and contact points can be marked to enable a more reliable determination of the stress distribution within each pebble. That data can then be correlated with crack statistics from mutually perpendicular cuts through the oriented specimens, as well

as a wider range of detailed microstructural observations of the type reported in chapter 4. The importance of pebble size, packing tightness, and sorting might be determined in a more quantitative sense.

2. Cathodoluminescence (C.L.) studies are needed to determine the importance of grain-scale microcracking as a precursor to pebble failure. Microcrack densities adjacent to microfaults, as assessed using both optical and SEM methods, appear lower in the pebbles than in experimental studies of cataclastic behavior in quartzites. Previous work on naturally deformed quartzites (Blenkinsop and Rutter, 1985) has shown that most extension cracks are not detected with these standard techniques (due to crack healing), but are readily observed with C.L.. The application of C.L. methods might enable the extension of the quantitative petrostructure analysis to higher magnifications with confidence. In turn, this will better constrain inferences regarding paleostress variations from pebble -to- pebble and locality -to- locality.

3. The marked variations in crack morphology, mode of failure, and initial microstructural parameters described in ch. 4 were observed from a limited set of only 10 pebbles. Using the digitizing and statistical programs developed in the course of this study, a much larger quantitative data base can be constructed quickly by simply collecting more samples. In this way, the quantitative correlation of initial microstructure properties with mechanical behavior can be placed on firmer footing. Grain size measurements from both unfaulted and faulted zones should be performed, and linked with modal analyses and x-ray diffractometry to determine the extent to which interstitial clay minerals influence mechanical behavior.

4. More detailed high-resolution microscopy is needed to further explore the importance of reactions involving clay minerals which line grain boundaries and fill cataclasite zones. Quantitative mineral analyses with the SEM might help to pinpoint areas where diffusive mass transfer has

occurred, and high voltage transmission electron microscopy (HVTEM) should be used to determine whether neomineralization occurs during shear deformation.

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APPENDIX A

A.1 Introduction

The collection of crack statistics can be a very tedious task, particularly when the number of samples comprising a complete study is large. The results of Chapter 3 broadly confirm the belief that crack and fracture patterns in naturally deformed rocks can provide useful paleostress orientation information, but they also highlight the importance of measuring large numbers of specimens both thoroughly and accurately. A large part of the effort which went into this research project was absorbed in writing and perfecting a set of BASIC computer programs which would help to make that task as painless as possible. A technique was developed which allows crack traces to be hand-digitized (either directly from photomicrograph mosaics or from overlay tracings), stored as sets of coordinates on floppy discs, and manipulated using a series of sorting and plotting routines. Analysis of a given crack set generally involved the following 6 procedures.

1. Crack traces were identified from photomicrograph mosaics and drawn onto sheets of tracing paper overlay.
2. Small tracings were enlarged using the departmental reprographic facilities, so that the area covered was slightly less than the size of an A4 (297mm x 210mm) sheet. Larger tracings were split into a series of A4 sheets in a grid-like fashion.
3. With the aid of an Acorn BBC Model "B" microcomputer (fitted with a Cambridge Computer Consultants Aries-B20 20K RAM expansion bit for additional memory space), and a British Micro "GRAFPAD" hand-digitizing pad, A4 size "crack

maps" were recorded onto individual permanent files and stored on floppy disk. The digitizing routine was supplied in machine code format with the "GRAFPAD", and a short BASIC procedure (ANGLE) appended to calculate angles and lengths of individual cracks.

4. Computer-generated maps were produced with a group of short plotting routines. Maps stored as single files were generated directly using the program MLOTG. For the larger maps, a slightly modified program was used; a series of PRINTMASTER commands supplied with the ROM utility for the BBC micro enable the sequential re-linking of files containing single A4 sheets of the original grid.

5. For the mosaic maps, the program WFCOR is used to assemble the grid of files into a global coordinate system representing the original photomosaic. A series of BASIC procedures test for crack continuity between adjacent files and apply "closeness of fit" criteria to relink single cracks that were separated during the process of grid formation.

6. The program HISTPL4 generates graphic plots of length and orientation statistics. It handles both raw data (from maps which fit on one A4 sheet), and processed data from global files generated using WFCOR. Length and orientation statistics are sorted into arrays and plotted using either histogram or rose diagram plotting routines, which utilize the high resolution graphics facilities of the BBC microcomputer.

Listings of the relevant BBC BASIC programs are included below. Some documentation is included within the program in the form of comment lines, and summary flow charts are provided to aid in the understanding of the general program structures. In addition, variables are

defined; BBC BASIC provides no cross listing of variables during the compilation stage, and it is hoped that the definitions I have provided will enable the transfer of programs to other programming languages, thus making them more amenable to wider use.

Many of the graphics routines are taken directly from Cryer et.al. (1983). Interested readers are referred to this text for detailed descriptions of individual procedures.

A.2 Digitizing routines

A.2.1 General Description

The programs DIGICRK and MACDIGI are designed for use with the "GRAFPAD". The two are identical except for a slight variation in the procedure ANGLE, concerning the way in which variables are read into the file entry containing an individual set of crack coordinates. MACDIGI is designed for use with maps which are either contained wholly on a single A4 sheet, or which comprise several connected sheets, but never split cracks from one sheet to the next. The distinction will become readily apparent from the description of the grid system which follows. The bulk of the program (lines 0-1940) comes directly from software supplied with the "GRAFPAD"; the code is far from transparent, and no flow charting is attempted. After a brief description of the method chosen for segmenting large maps into a grid pattern, the procedure ANGLE will be documented as it appears in both DIGICRK and MACDIGI. Essential differences between the two are noted.

A.2.2 The Grid System

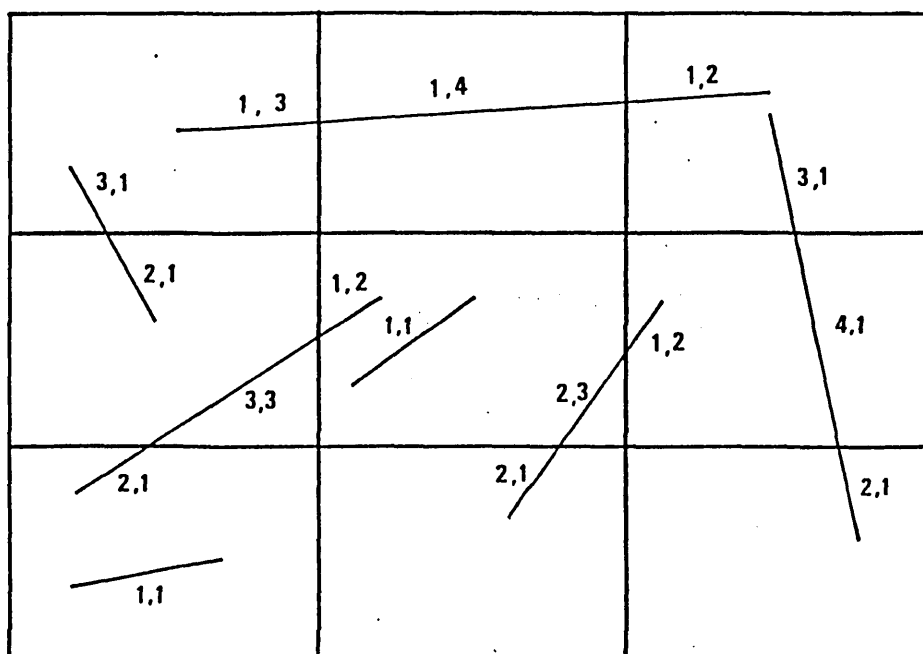
When digitizing a map containing linear features,

it is often impractical to reprographically reduce the map such that it fits wholly within the dimensions of the "GRAFPAD" coordinates (297 x 210mm). Generally, this situation arises when mapped lengths are short, and reduction shrinks them to less than the minimum resolvable length of the pad (MRL; see Chapter 3). A grid system was thus developed to allow large sheets to be broken into segments, digitized on A4 sheets, and pieced together using a file management system. Inevitably, the segmentation results in the splitting of long cracks, and a set of continuity tests were developed to allow a given file to be searched for cut cracks. Where possible, these were then spliced together to restore their original lengths in the global file containing the crack entries for all individual A4 sheets.

To facilitate this splicing procedure, a pair of integer codes was attached to the file entry of a single crack. Figure A.1 summarizes the codes and their meanings, and indicates the code entries which would be required for an arbitrary crack map which has been divided into a 3x3 grid. The codes are entered in pairs (separated by a comma, and followed by <RETURN>), after an appropriate prompt from within the digitizing program. The variable CODE1 contains the code for the vertical continuity test, with the variable CODE2 holding the corresponding code for the test of horizontal continuity. These are subsequently examined in the program WFCOR, which contains the actual testing and splicing procedures.

A.2.3.1 Program MACDIGI

Program Listing:



Vertical Test
(CODE1)

- 1.No Continuity
- 2.Top Continuity
- 3.Bottom Continuity
- 4.Throughgoing

0.Reset Value

Horizontal Test
(CODE2)

- 1.No Continuity
- 2.Left Continuity
- 3.Right Continuity
- 4.Throughgoing

0.Reset Value

Figure A.1. Arbitrary 3x3 Map grid, illustrating a typical coding sequence. Table summarizes the integer continuity codes required for use with program WFRCOR.

A.2.3.2 Program DIGICRK

Except for the inclusion of crack code variables, the program is identical to MACDIGI. The amended version of PROCANGLE is included to illustrate the minor changes involved.

Listing of PROCANGLE:

```

>
2000DEFPROCANGLE
2005 PL=INKEY(50)
2010IF PQX=1 THEN GOTO 2020 ELSE GOTO 2040
2020 PRINT;TAB(0,23);"FIRST POINT"
2025IF ?UX=0 THEN GOTO 2030 ELSE GOTO2210
2030MOVE!XX*4,!YY*4:PQX=2:AXX=!XX:AYX=!YY:GOTO 2210
2040 PRINT;TAB(0,23);"SECOND POINT"
2045IF ?UX=0THEN GOTO 2050 ELSE GOTO2210
2050DRAW!XX*4,!YY*4:PQX=1:BX=!XX:BY=!YY
2055IF(BX-AX)=0 THEN GOTO 2067
2060 THETA=DEG(ATN(ABS((BY-AY)/(BX-AX)))) :GOTO 2070
2067 THETA=90 : GOTO 2070
2070 LGTH=((BY-AY)*2)+((BX-AX)*2)
2075 LGTH=SQR(LGTH)
2076 INPUTTAB(0,2);"INPUT CRACK CODES -CODE1X, CODE2X",CODE1X, CODE2X
2077 PRINTTAB(0,2);"
2180 PRINTTAB(0,5);"DATA OK? Y-N-S?"
2185 IF GET$="Y" THEN GOTO 2190 ELSE GOTO 2186
2186 IF GET$="S" THEN GOTO 2205 ELSE GOTO 2200
2190 PRINTPF, AXX, BXX, AYY, BYY, THETA, LGTH, CODE1X, CODE2X
2195 NNX=NNX+1
2196 PRINTTAB(0,8);"LAST DATA STORED=";NNX
2197 PRINTTAB(0,23);"
2200 PQX=1:PRINTTAB(0,5);"
2205 CLOSEFO:STOP
2210 ENDPROC

```

*:GOTO 2210

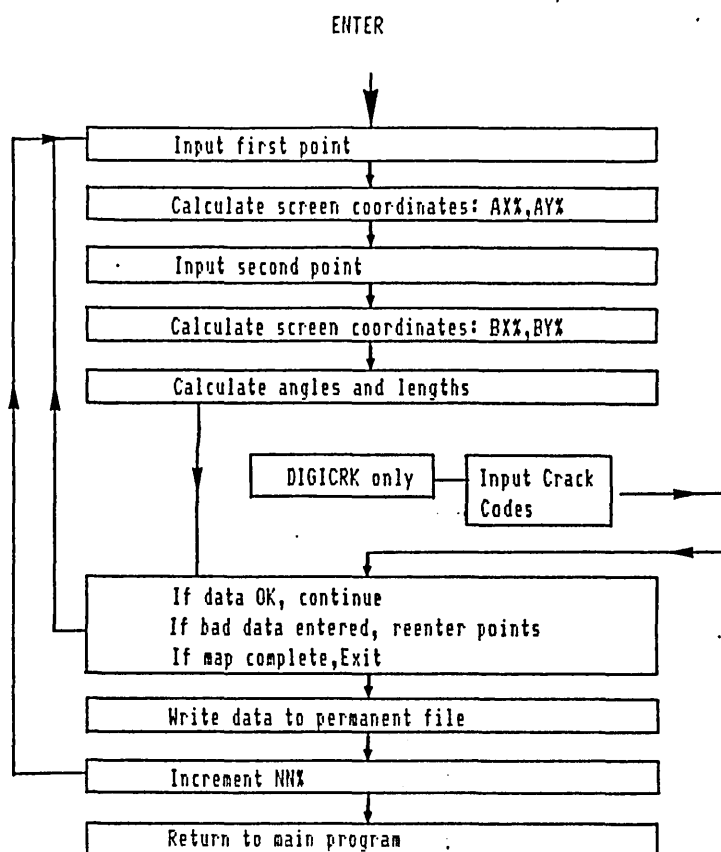


Fig. A-2 Summary flow chart for PROC ANGLE (in MACDIGI)

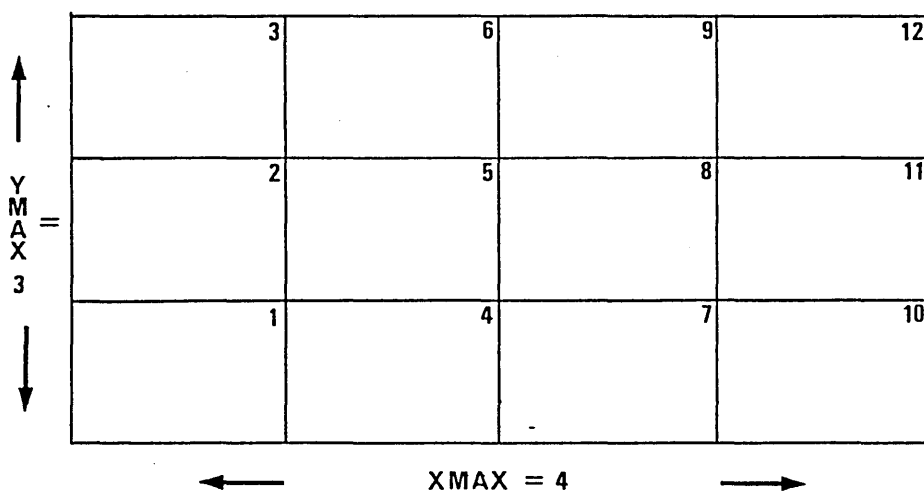


Fig. A-3 Arbitrary 4x3 grid illustrating correct file entry sequence

Variable Definitions: PROCANGLE (from MACDIGI)

!X%	X GRAFPAD coordinate for crack endpoint (0,320)
!Y%	Y GRAFPAD coordinate for crack endpoint (0,255)
AX%	X screen coordinate for first crack endpoint recorded (0,1280)
AY%	Y screen coordinate for first crack endpoint recorded (0,1020)
BX%	X screen coordinate for second crack endpoint recorded
BY%	Y screen coordinate for second crack endpoint recorded
GET\$	Holds data check/stop character (Y/N/S)
LGTH	Crack length
NN%	Counter: number of cracks recorded
PF	Permanent file variable for data storage
PL	Time lag (safety device)
PQ%	Determines point to be stored
THETA	Crack orientation in degrees (0-90 only)
U%	Drawing code

Variable Definitions: PROCANGLE in DIGICRK

Variable listings are identical to MACDIGI, except for the inclusion of crack codes:

CODE1%	Vertical continuity code
CODE2%	Horizontal continuity code

A.3 Program MPLOTGI

The listing for MPLOTGI is largely self-explanatory, and provided only for the sake of completeness. Values from the digitizing sequence are read in from a designated permanent file, scaled to provide a full-sized, geometrically accurate hardcopy, and plotted. The WINDOW and GDUMP facilities provided with PRINTMASTER enable the control of printout size and placement from within the program. Appropriate codes are listed in the PRINTMASTER user guide supplied with the utility.

Program Listing:

```

>
10 MODEO
20 INPUT"ENTER DATA FILE NAME" NAME$
30 CLS
40 Q=OPENIN NAME$
50 MOVE 0,0
60 DRAW 0,1023
70 DRAW 1060,1023
80 DRAW 1060,0
90 DRAW 0,0
100 REPEAT
110 INPUTEQ,AXX,BXX,AYX,BYX,THETA,LGTH,CODE1X,CODE2X
120 MOVE INT(AXX*4*.825),AYX*4
130 DRAW INT(BXX*4*.825),BYX*4
140 UNTIL EOFQ
150 CLOSEQ
160 *WINDOW
170 *GDUMP 0 0 1 1 20
180STOP

```

A.4 Program WFCOR

The program WFCOR assembles the grid of individual files from large maps into a global network, and checks for crack continuity between files. When digitizing one map, the program can be bypassed completely; the plotting facilities of HISTPL4 should be called directly. With the 20K RAM expansion, at least 600 individual crack entries can be combined into one global file without exceeding the memory limitations of the BBC "Model B", using graphics MODE 1. For "Model B's" not fitted with an expansion bit, MODE 7 is recommended, though the user may find that existing memory permits the storage of a reduced number of crack entries.

The program can accomodate a range of grid dimensions, subject to the memory limitations noted above. Because of difficulties encountered with "end-of-file" markers, it was necessary to enter individual filesizes as input parameters. These are best recorded immediately after digitizing a given map. The initialization sequence of the program also requires the map grid dimensions and number of files as input data. For the continuity test sequence to work properly, the input data must be specified in the following form:

1. Grids must be of regular integer dimensions (ie. rectangular or square)
2. Filenames and sizes must be entered sequentially, in the position in which they appear in the initial grid. The first file entered must be in the bottom left hand corner of the global grid. Subsequent entries proceed vertically to the top of the grid, at which point the file at the bottom of the column to the right is entered. Figure A.3 shows a typical 4x3 grid, and indicates the correct numbering sequence for file entry.

The sole remaining input parameter, the name of

the global data file. must be entered after the crack continuity tests are complete.

Program Listing:

```

10ex=800508
20MODE1
30REM correlation program
40DIM A$(10),FSIZE$(10),AX$(600),BX$(600),AY$(600),BY$(600),THETA(600),LGTH(600),CODE1$(600),CODE2$(600),MAP$(10)
50INPUT "ENTER NUMBER OF FILES",NUMF
60 INPUT "ENTER GRID DIMENSIONS;XMAX,YMAX:",XMAX,YMAX
70FOR MJ=1 TO NUMF
80INPUT "FILENAME,FILESIZE??",A$(MJ),FSIZE$(MJ)
90NEXT MJ
100CLS
110PRINT SPC(3);"AX";SPC(6);"BX";SPC(6);"AY";SPC(6);"BY";SPC(5);"CODE1";SPC(3);"CODE2";SPC(3);"THETA";" LENGTH"
120CTR=0
130PNT=0
140FOR MJ=1 TO NUMF
150REM calculate present row and column within map grid
160NX=INT(((MJ-1)/3))+1
170NY=MJ-3*(NX-1)
180Q=OPENIN(A$(MJ))
190REPEAT
200CTR=CTR+1
210PNT=PNT+1
220INPUT Q,AX$(PNT),BX$(PNT),AY$(PNT),BY$(PNT),THETA(PNT),LGTH(PNT),CODE1$(PNT),CODE2$(PNT)
230 IF BY$(PNT)<AY$(PNT) AND AX$(PNT) <= BX$(PNT) THEN THETA(PNT)=-THETA(PNT)
240IF AY$(PNT)<BY$(PNT) AND AX$(PNT)>=BX$(PNT) THEN THETA(PNT)=-THETA(PNT)
250 IF THETA(PNT)=-90 THEN THETA(PNT)=90
260REM establish global coordinate system
270AX$(PNT)=AX$(PNT)+(NX-1)*317
280BX$(PNT)=BX$(PNT)+(NX-1)*317
290AY$(PNT)=AY$(PNT)+(NY-1)*250
300BY$(PNT)=BY$(PNT)+(NY-1)*250
310REM adjust entries so that AX always less than BX.
320IF AX$(PNT)<= BX$(PNT) THEN GOTO 360
330TEMPX=AX$(PNT):TEMPY=AY$(PNT)
340AX$(PNT)=BX$(PNT):AY$(PNT)=BY$(PNT)
350BX$(PNT)=TEMPX:BY$(PNT)=TEMPY
360PRINT AX$(PNT),BX$(PNT),AY$(PNT),BY$(PNT),CODE1$(PNT),CODE2$(PNT),THETA(PNT),LGTH(PNT)
370UNTIL CTR=FSIZE$(MJ)
380CLOSE Q
390MAP$(MJ)=CTR
400PRINT "
410PRINT "MAP";MJ;" CONTAINS ";MAP$(MJ);" ELEMENTS"
420CTR=0
430NEXT MJ
440REM enter test sequence to test crack continuity
450ITEM=0:PNT=0
460HALT =NUMF-1
470REM loops over each grid array
480FOR MJ=1 TO HALT
490NX= INT(((MJ-1)/3))+1
500NY= MJ-3*(NX-1)
510ITEM = ITEM + MAP$(MJ)
520IF NY=YMAX THEN GOTO 610
530REPEAT
540PNT =PNT + 1
550REM vertical continuity sequence
560IF CODE1$(PNT)=2 OR CODE1$(PNT)=1 THEN PROCVERTES
570UNTIL PNT=ITEM
580REM horizontal test sequence
590IF NX=XMAX THEN GOTO 650
600PNT=ITEM-MAP$(MJ)
610REPEAT
620PNT=PNT+1
630IF CODE2$(PNT)>2 THEN PROCHORTES
640UNTIL PNT=ITEM
650NEXT MJ
660ITEM = ITEM +MAP$(NUMF)
670PNT=0
680SUM=0

```

```

690REM write updated crack data to new file "global"
700PRINT " ":PRINT " ":PRINT TAB(15)"GLOBAL DATA"
710PRINT "AX","BX","AY","BY","THETA","LENGTH"
720 INPUT"ENTER GLOBAL FILE NAME: ",C$
730 PF=OPENOUT(C$)
740REPEAT
750PNTX=PNTX +1
760IF CODE1X(PNTX)=0 OR CODE2X(PNTX)=0 THEN GOTO 800
770SUMX=SUMX +1
780PRINT AX(PNTX),BX(PNTX),AY(PNTX),BY(PNTX),THETA(PNTX),LGTH(PNTX)
790PRINTPF,AX(PNTX),BX(PNTX),AY(PNTX),BY(PNTX),THETA(PNTX),LGTH(PNTX)
800UNTIL PNTX=ITEM
810PRINT"GLOBAL FILE CONTAINS ";SUMX;" CRACK VALUES"
820 CLOSE[PF
830END
840DEF PROCVERTES
850REM fix global counter at block to be tested
860POINTX=0
870FOR K=1 TO MJ
880POINTX=POINTX + MAPX(K)
890NEXT K
900YTESTB= MJ+1
910YTESTB=POINTX + MAPX(YTESTB)
920REPEAT
930POINTX= POINTX+1
940REM crack with bottom continuity to match?
950IF CODE1X(POINTX)>2 THEN PROCYCHECK
960UNTIL POINTX=YTESTB
970ENDPROC
980DEF PROCYCHECK
990IF (BYX(PNTX)>AYX(PNTX)) THEN UX=0 ELSE UX=1
1000IF (BYX(POINTX)>AYX(POINTX)) THEN PX=0 ELSE PX=1
1010IF UX=0 AND PX=0 THEN GOTO 1040
1020IF UX=1 AND PX=1 THEN GOTO 1150
1030GOTO 1250
1040IF ABS(BX(PNTX)-AX(PNTX))>4 THEN GOTO 1250
1050IF ABS(THETA(PNTX)-THETA(PNTX))>20 THEN GOTO 1250
1060AX(PNTX)=AX(PNTX): AY(PNTX)=AY(PNTX)
1070LGTH(PNTX)=LGTH(PNTX) + LGTH(PNTX)
1080IF CODE1X(PNTX)=4 AND CODE1X(PNTX)=4 THEN CODE1X(PNTX)=4
1090IF CODE2X(PNTX)>2 OR CODE2X(PNTX)>2 THEN CODE2X(PNTX)=3
1100REM reset pnt% values to zero for all arrays
1110AX(PNTX)=0:BX(PNTX)=0:AY(PNTX)=0:BY(PNTX)=0
1120THETA(PNTX)=0:LGTH(PNTX)=0:CODE1X(PNTX)=0:CODE2X(PNTX)=0
1130PRINT " ":PRINT"CRACK ";PNTX;" JOINED TO CRACK ";POINTX:PRINT" "
1140GOTO 1250
1150IF ABS(AX(PNTX)-BX(PNTX))>4 THEN GOTO 1250
1160IF ABS(THETA(PNTX)-THETA(PNTX))>20 THEN GOTO 1250
1170BX(PNTX)=BX(PNTX):BY(PNTX)=BY(PNTX)
1180LGTH(PNTX)=LGTH(PNTX) + LGTH(PNTX)
1190IF CODE1X(PNTX)=4 AND CODE1X(PNTX)=4 THEN CODE1X(PNTX)=4
1200IF CODE2X(PNTX)>2 OR CODE2X(PNTX)>2 THEN CODE2X(PNTX)=3
1210REM reset pnt% values to zero for all arrays
1220AX(PNTX)=0:BX(PNTX)=0:AY(PNTX)=0:BY(PNTX)=0
1230THETA(PNTX)=0:LGTH(PNTX)=0:CODE1X(PNTX)=0:CODE2X(PNTX)=0
1240PRINT " ":PRINT"CRACK ";PNTX;" JOINED TO CRACK ";POINTX:PRINT" "
1250ENDPROC
1260DEF PROCHORTES
1270LIMIT=0
1280ADJAC=0
1290REM fix global counter at start of test Column
1300XTESTA=NX*3
1310FOR M=1 TO XTESTA
1320ADJAC=ADJAC+MAPX(M)
1330NEXT M
1340BOUND=ADJAC
1350ADJAC=ADJAC+1
1360FOR L=1 TO NYX
1370S= (NX*3) +L
1380LIMIT=LIMIT+MAPX(S)
1390NEXT L
1400UPLIM =LIMIT + BOUND
1410FOR T=ADJAC TO UPLIM
1420IF CODE2X(T)=2 OR CODE2X(T)=4 THEN PROCXCHECK
1430NEXT T
1440ENDPROC
1450DEF PROCXCHECK
1460IF ABS(BYX(PNTX)-AYX(T))>4 THEN GOTO 1550
1470IF ABS(THETA(PNTX)-THETA(T))>15 THEN GOTO 1550
1480AX(T)=AX(PNTX):AY(T)=AY(PNTX)
1490LGTH(T)=LGTH(PNTX) + LGTH(T)
1500IF CODE2X(T)=4 AND CODE2X(PNTX)=4 THEN CODE2X(T)=4
1510REM null all arrays for pnt%
1520AX(PNTX)=0:BX(PNTX)=0:AY(PNTX)=0:BY(PNTX)=0
1530THETA(PNTX)=0:LGTH(PNTX)=0:CODE1X(PNTX)=0:CODE2X(PNTX)=0
1540PRINT " ":PRINT"CRACK ";PNTX;" JOINED TO CRACK ";T:PRINT" "
1550ENDPROC

```

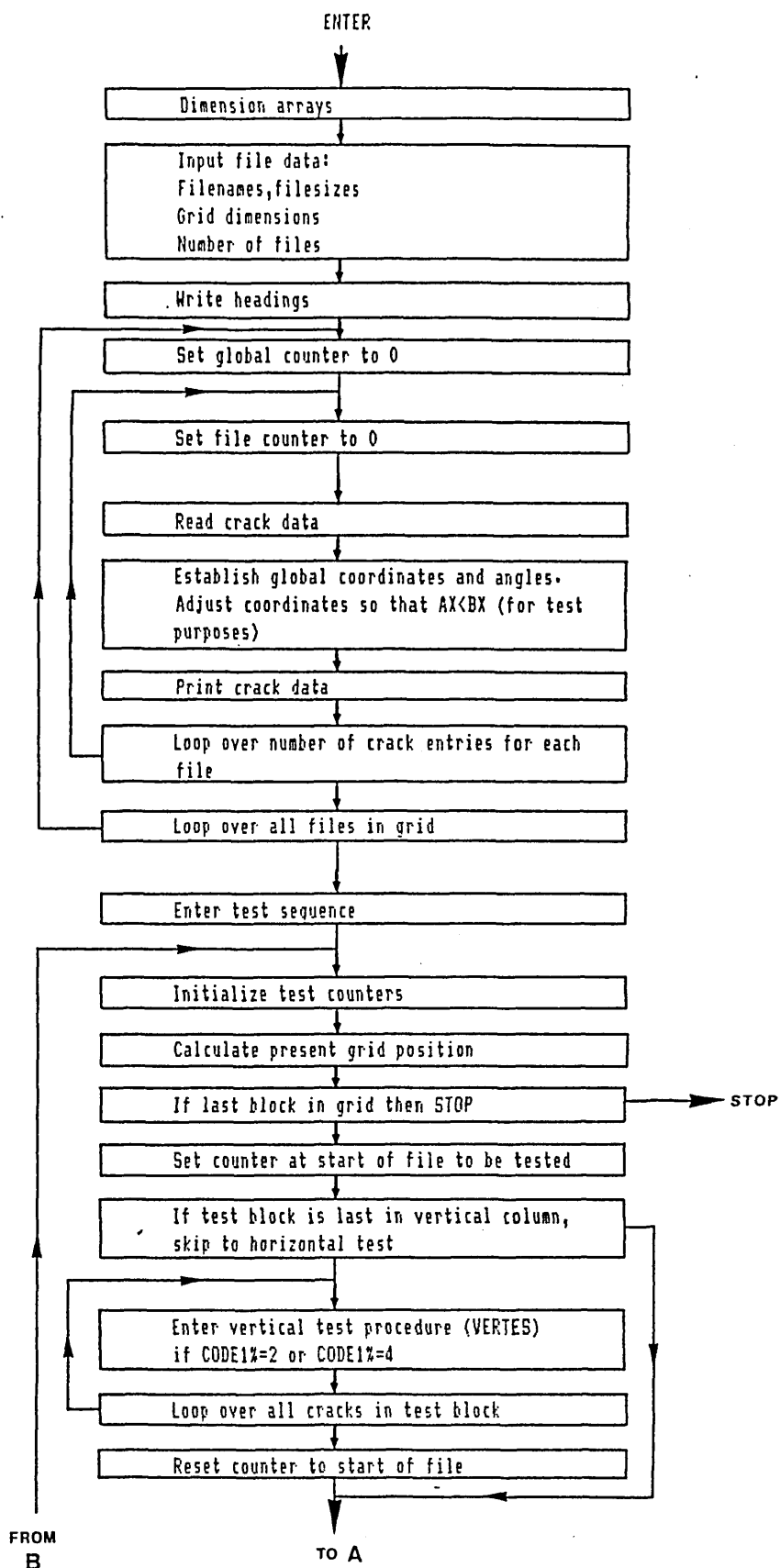


Fig.A.4 Summary flow chart for program WFRCOR

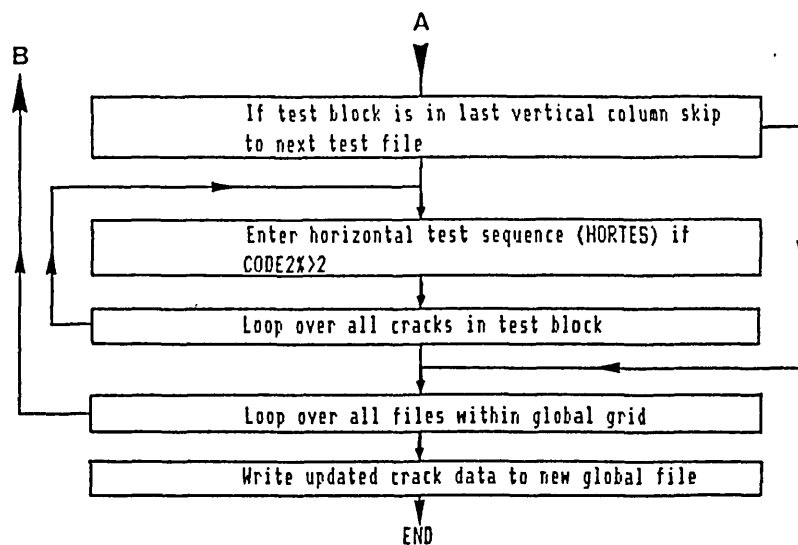


Fig.A.4 Summary flow chart for program WFRCOR

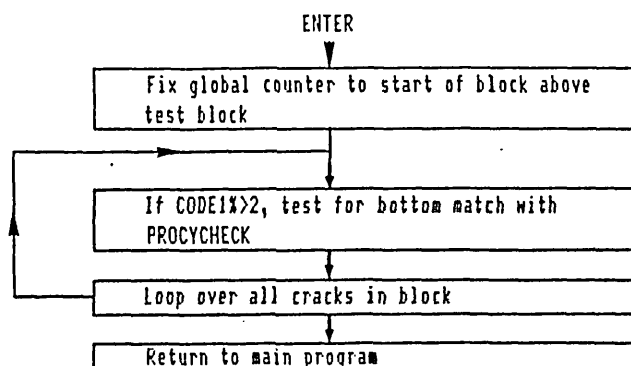
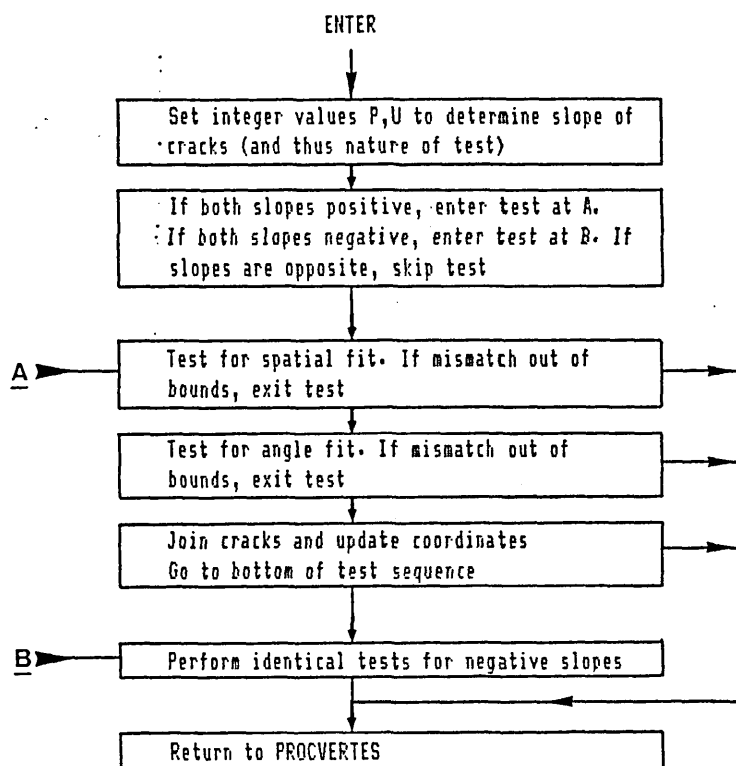
PROCVERTESPROCYCHECK

Fig.A.5 Summary flow charts for PROCVERTES and PROCYCHECK

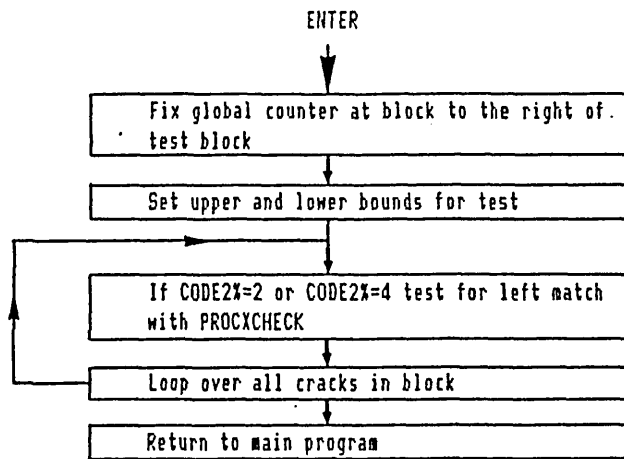
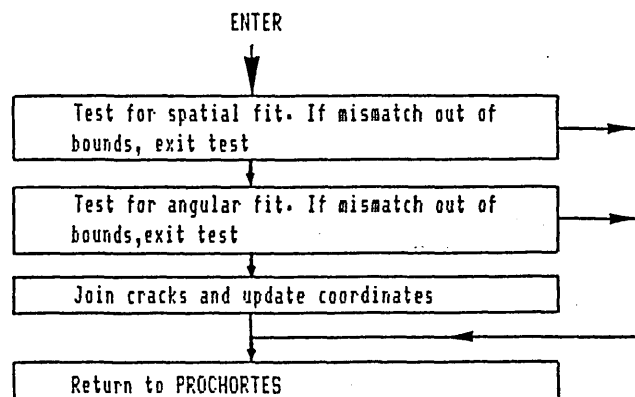
PROCHORTESPROCXCHECK

Fig.A.6 Summary flow chart for PROCHORTES and PROCXCHECK

Variable Definitions: WFRCOR

Array Variables:

A\$	Individual filenames
AX%	First X coordinate of cracks
AY%	First Y coordinate of cracks
BX%	Second X coordinate of cracks
BY%	Second Y coordinate of cracks
CODE1%	Integer codes for vertical continuity test
CODE2%	Integer codes for horizontal continuity test
FSIZE%	File sizes for each individual file
LGTH	Crack length values
MAP%	Filesizes in proper sequential order
THETA	Crack angle values

Single value variables in main program:

C\$	Global crack file name
CTR%	Counter in global coordinate sequence
HALT	Number of last testable file in grid
ITEM	Upper bound within testing block
MJ	Counter within test sequence
NUMF	Number of files in grid
PF	Permanent file value for data storage
PNT%	Global crack counter
Q	Permanent file value in input sequence
SUM%	Counter in output sequence
TEMPX%	X storage value for switching AX,BX
TEMPY%	Y storage value for switching AY,BY
XMAX%	X grid dimension
YMAX%	Y grid dimension

Variables local to vertical test sequence (VERTES):

K	Counter in initializing sequence
P%	Crack slope variable - negative slope
POINT%	Crack counter within upper testing block

Table A.2 Variable descriptions: Program WFRCOR

UX	Crack slope variable - positive slope
YTESTB	Upper limit of upper test block

Variables local to horizontal test sequence (HORTES):

ADJAC	Lower bound within tested block
BOUND	Stores ADJAC value before updating proceeds
L	Counter in test sequence
LIMIT	Counter position within present column
S	File counter within present column
T	Counter within tested block
UPLIM	Upper bound within tested block
XTESTA	Position of uppermost file in designated column

A.5 Program HISTPL4

Using program HISTPL4, The assembled crack data can be sorted and plotted in either rose diagram or histogram format. A range of input parameters (filename, filesize, crack magnification, and number of histogram graduations) must be specified, after appropriate prompts. Data which has come directly from the MACDIGI generating procedure is processed to ensure that angular values are corrected; data which has been processed using WFCOR is sorted directly. An integer code (1 for processed data, 2 for raw) is specified after the preceding prompt.

As with the program WFCOR, the actual number of cracks that can be analysed will depend upon the particular memory limitations of the computer being used. With the RAM expansion, a maximum of 500 cracks can be stored and processed using the highest resolution graphics mode (MODE 0). Hardcopies of screen plots are generated using the PRINTMASTER screen dumping facilities; the program provides the user with the option of bypassing the printer plots. One minor point of confusion may arise after the final plot, the length histogram, is produced. No prompt is generated onscreen, but a hardcopy can still be generated using the "Y" key.

In addition to the program listing and variable definitions, a summary flowchart of the basic program structure is provided. Only a detailed description of the rose diagram routine PROCROSE is presented; for descriptions of the other graphics procedures, the reader is referred to the text by Cryer et. al.(1983).

Program Listing:

```

10 MODE0
20 OPEN # HISTOGRAM PLOTTING ROUTINE#
30 INPUT "ENTER NUMBER OF CRACK ENTRIES, FOLLOWED BY DATA FILE NAME",FSIZES,FINAME$
40 INPUT "ENTER MAP MAGNIFICATION ",MAG
50 INPUT "ENTER NUMBER OF ANGLE GRADUATIONS REQUIRED",MUMTHE
60 INPUT "ENTER NUMBER OF LENGTH GRADUATIONS REQUIRED",MUMLEN
70 INPUT "IS DATA GLOBAL (i.e. TRUE ANGLES)? IF YES (ENTER 1) ELSE ENTER 0",ICD
80 IF MUMLEN<MUMTHE THEN SPACE=MUMLEN+1 ELSE SPACE=MUMTHE+1
90 DIM A$(FSIZES),B$(FSIZES),X$(FSIZES),Y$(FSIZES),THETA(FSIZES),LGTH(FSIZES),SCANT$(MUMTHE),SCANL$(MUMLEN),X$(SPACE),Y$(SPACE),
M$(150),MY$(150),DENS(MUMTHE),LGTHSQ(FSIZES)
100 REM *INITIALIZE ARRAYS*
110 FOR M$=0 TO MUMTHE
120 SCANT$(M$)=0
130 DENS(M$)=0
140 NEXT M$
150 FOR M$=0 TO MUMLEN
160 SCANL$(M$)=0
170 NEXT M$
180 REM *INPUT DATA*
200 OPEN IN$(FINAME$)
210 FOR J$=1 TO FSIZES
220 INPUT Z, A$(J$), B$(J$), X$(J$), Y$(J$), THETA(J$), LGTH(J$)
230 IF ICD=1 THEN GOTO 310
240 REM *CORRECT ANGLES*
250 IF A$(J$)<B$(J$) THEN GOTO 290
260 TEMP1=A$(J$):TEMPY=Y$(J$)
270 A$(J$)=B$(J$):X$(J$)=X$(J$):Y$(J$)=Y$(J$)
280 B$(J$)=TEMP1:BY$(J$)=TEMPY
290 IF BY$(J$)<A$(J$) THEN THETA(J$)=THETA(J$)-THETA(J$)
300 REM *CORRECT AND SQUARE LENGTHS*
310 LGTH(J$)=(LGTH(J$)+.75)/MAG
320 LGTHSQ(J$)=(LGTH(J$)+.75/MAG)^2
330 TTL=TTL+LGTHSQ(J$)
340 NEXT J$
350 CLOSE IN$
360 REM *SORT THETA ARRAY FOR PLOTTING *
370 REM *SET UP SECTORS*
380 BRACKET=(180/MUMTHE)
390 FOR J$=1 TO FSIZES
400 IF THETA(J$)>0 THEN TEST=(180-THETA(J$))/BRACKET ELSE TEST=-THETA(J$)/BRACKET
410 TESTA=INT(TEST)+1
420 SCANT$(TESTA)=SCANT$(TESTA)+1
430 DENS(TESTA)=DENS(TESTA)+(LGTHSQ(J$)/TTL)*100
440 NEXT J$
450 FOR K$=1 TO MUMTHE
460 PP1="SCANT(;"K$;" ) = "SCANT$(K$); " DENS(;"K$;" ) = "DENS(K$)
470 NEXT K$
480 REM *SORT LENGTH ARRAY FOR PLOTTING *
490 REM *SEARCH FOR MAX LENGTH OF ARRAY*
500 RHAI=0
510 FOR J$=1 TO FSIZES
520 IF LGTH(J$)>LHAI THEN LHAI=LGTH(J$)
530 NEXT J$
540 REM *SET UP SECTORS*
550 WINDOW=LHAI/MUMLEN
560 FOR J$=1 TO FSIZES
570 TEST=LGTH(J$)/WINDOW
580 TESTA=INT(TEST)+1
590 IF LTESTA=MUMLEN THEN LTESTA=LTESTA-1
600 TESTA=LTESTA+1
610 IF LTESTA=MUMLEN THEN PRINT "LIMIT OF ARRAY SCANL EXCEEDED"
620 SCANL$(LTESTA)=SCANL$(LTESTA)+1
630 NEXT J$
640 PRINT " "
650 FOR K$=1 TO MUMLEN
660 PP1="SCANL(;"K$;" ) = "SCANL$(K$)
670 NEXT K$
680 REM *PLOTTING ROUTINES*
690 REM * ANGLE PLOT *
700 PROCROSE1
710 PROCROSE2
720 FOR I$=1 TO MUMTHE
730 (I$)=SCANT$(I$):X(I$)=I$*BRACKET
740 NEXT I$
750 (0)=MUMTHE *I:Y(MUMTHE+1)=0:IN=BRACKET
760 CLG
770 US=0
780 PROC COMBO
790 REM * LENGTH PLOT *
800 US=1
810 FOR I$=1 TO MUMLEN
820 Y(I$)=SCANL$(I$):I(I$)=I$*WINDOW
830 NEXT I$
840 (0)=MUMLEN *I:Y(MUMLEN+1)=0:IN=WINDOW
850 LG
860 CLS
870 PROC COMBO
880 PRINT "HARD COPY? Y/N? "
890 IF GET$="Y" THEN PROC DUMP2
900 IF GET$="N" THEN PRINT "
910 END
920 DEF PROC COMBO
930 VDU1,0,40;
940 PROC SCALE
950 PROC HISTO
960 COL 0,3
970 PROC A15
980 PROC GRADUATE
990 PROC NUMBER
1000 IF US=0 THEN PROC NAME1("CRACK ORIENTATION") ELSE PROC NAME1("CRACK LENGTH --");
1010 PROC NAMEY("NUMBER")
1020 VDU5: MOVE 2000,2000
1030 END PROC
1040 DEF PROC ROSE1
1050 CLS
1060 RHAI=0
1070 FOR KLS=1 TO MUMTHE
1080 IF SCANT$(KLS)>RHAI THEN RHAI=SCANT$(KLS)
1090 NEXT KLS
1100 PRINT TAB(0,1) "RHAI= ";RHAI
1110 CHAI=INT((RHAI-1)/10)+1
1120 PRINT TAB(0,2) "CHAI= ";CHAI
1130 SCF=INT(500/(CHAI+10))
1140 PRINT TAB(0,3) "MAPE ";FINAME$
1150 PRINT TAB(0,4) "E OF CRACKS= ";FSIZES
1160 MOVE 040,200
1170 DRAW 1240,200
1180 INCH=0
1190 FOR JKI=1 TO CHAI

```

```

1200 PROCCIRCLE
1210 NEXT J=1
1220 YDU29,640,200;
1230 MOVE 0,0
1240 PHI=0
1250 FOR LX=1 TO MUMTHE
1260 DRAW -INT(SCANTI(LX))*COS(RAD(PHI))+SCF*.825,INT(SCANTI(LX))*(SIN(RAD(PHI))+SCF)
1270 DRAW -INT(SCANTI(LX))*COS(RAD(PHI+180/MUMTHE))+SCF*.325,INT(SCANTI(LX))*(SIN(RAD(PHI+180/MUMTHE))+SCF)
1280 PHI=PHI+180/MUMTHE
1290 NEXT LX
1300 PFCNUMPOSE
1310 VGJ4
1320 PRINTTAB(20,30)"CRACK NUMBER VS. ORIENTATION(DEGS)"
1330 *WINDOW
1340 PRINTTAB(30,32)"HARDCOPY" Y/N? "
1350 IF GETB="Y" THEN PROCUMFI
1360 PRINTTAB(30,32)"
1370 ENDPROC
1380 DEFPROCROSE2
1390CLS
1400RMAI=0
1410FOR KLI=1 TO MUMTHE
1420IF DENS(KLI)>RMAI THEN RMAI=DENS(KLI)
1430NEXTKLI
1440PRINTTAB(0,1)"RMAI= "RMAI
1450CHAI=INT((RMAI-1)/10)+1
1460PRINTTAB(0,2)"CHAI= "CHAI
1470 SCF=INT(500/(CHAI+10))
1480 PRINTTAB(0,3)"MAP: "FINAMES
1490 YDU29,0,0;
1500PRINTTAB(0,4)"# OF CRACKS= "FSIZES
1510MOVE 040,200
1520DRAW 1240,200
1530INCE=0
1540FOR JKI=1 TO CHAI
1550PROCCIRCLE
1560NEXT JKI
1570 YDU29,640,200;
1580MOVE 0,0
1590PHI=0
1600FOR LX=1 TO MUMTHE
1610DRAW -INT(DENS(LX))*COS(RAD(PHI))+SCF*.25,INT(DENS(LX))*SIN(RAD(PHI))+SCF
1620DRAW -INT(DENS(LX))*COS(RAD(PHI+180/MUMTHE))+SCF*.825,INT(DENS(LX))*SIN(RAD(PHI+180/MUMTHE))+SCF
1630PHI=PHI+180/MUMTHE
1640NEXT LX
1650PFCNUMPOSE
1660VDUA
1670 PRINTTAB(15,30)"CPAC: DENSITY% OF TOTAL VS. ORIENTATION(DEGS)"
1680*WINDOW
1690 PRINTTAB(30,32)"HARDCOPY" Y/N? "
1700 IF GETB="Y" THEN PROCUMFI
1710 PRINTTAB(30,32)"
1720 ENDPROC
1730 DEFPROCSCALE
1740"ST=X/I) : LX=ST : SY=Y(I) : LY=SY
1750FOR I=1 TO I(0)
1760IF SY>(I) THEN SY=I(I)
1770IF LX>(I) THEN LX=I(I)
1780IF SY>Y(I) THEN SY=Y(I)
1790IF LX>X(I) THEN LX=X(I)
1800NEXT I
1810PROCSCALE2"ST, LX) : ST=X : LX=L
1820 ST=X : ST : CBX= CBX
1830PROCSCALE2"ST, LY) : SY=X : LY=L
1840 SY=X : SY : CBY= CBY
1850 X=1000/(LX-ST) : Y=900/(LY-SY)
1860 CONVM=150-ST : X : CONVM=100-SY : Y
1870ENDPROC
1880DEF FN CVI(G) : X=X+CONVM
1890DEF FN CVY(G) : Y=Y+CONVM
1900DEF PROCSCALE2(L,H) :X=X+10101090A
1910IF L=0 AND L<H/3 THEN L=0 ELSE IF H=0 AND H<L/3 THEN H=0
1920 LL=VAL(LEFT$(STR(L),INSTR(STR(L),"E")-1))
1930 LH=VAL(LEFT$(STR(H),INSTR(STR(H),"E")-1))
1940 PL=VAL(MID$(STR(L),INSTR(STR(L),"E")+1))
1950 LH=LH*10*(VAL(MID$(STR(H),INSTR(STR(H),"E")+1))-PL)
1960 D=LH-LL
1970IF D<3 THEN REPEAT D=D+10 : PL=PL-1 : LL=LL+10 : LH=LH+10 UNTIL D<3
1980IF D>30 THEN REPEAT D=D/10 : PL=PL+1 : LL=LL/10 : LH=LH/10 UNTIL D<30
1990 LL=INT(LL*.1) : LH=INT(LH*.5)
2000BX=410 : CBX=SGN(LL)*(VAL(PIGHT$(STR(LL),1)))+1)
2010 S=VAL(STR(LL)*E+STR(PL))
2020 L=VAL(STR(LH)*E+STR(PL)) : ST=ABS(L-S)/(LH-LL)
2030ENDPROC
2040DEF PROCCHISTO
2050 C=1
2060FOR A=1 TO I(0)-1
2070GCOLO, C : C=C+1 : IF C>2 THEN C=1
2080 XL=FN CVI(X(A)) : YL=FN CVI(Y(A))
2090 YH=FN CVY(Y(A))
2100 YB=FN CVY(0)
2110MOVE XL,YB : MOVE XL,YH
2120PLOT 85, XL,YB : PLOT 85, XL,YH
2130GCOL 0,1
2140MOVE XL,YB : DRAW XL,YB
2150DRAW XL,YH : DRAW XL,YH : DRAW XL,YB
2160NEXT A
2170ENDPROC
2180DEF PROCACATES
2190 I=0 : Y0=0
2200IF ST=0 THEN I=0 : ST ELSE IF L<0 THEN I=0 : LY
2210IF SY=0 THEN I=0 : SY ELSE IF LY<0 THEN I=0 : LY
2220MOVE FN CVI(SI),FN CVI(Y0) : DRAW FN CVI(LI),FN CVI(Y0)
2230MOVE FN CVI(SI),FN CVI(SY) : DRAW FN CVI(LI),FN CVI(LY)
2240ENDPROC
2250DEF PROCACQUATE
2260FOR I=1 TO LX+1 : STX STEP STX
2270IF CBXMOD5=0 THEN DT=16 ELSE DT=8
2280 CBX=CBX+1 : PROCPOINT(I,Y0) : NEXT I
2290FOR Y=SY TO LY+1 : STY STEP STY
2300IF CBYMOD5=0 THEN DT=16 ELSE DT=8
2310 CBY=CBY+1 : PROCPOINT(I0,Y) : NEXT Y

```

```

2320DEF PROCPOINT(A,B)
2330 MOVEFN'CVX(A)-DTA, FN'CVY(B):DRAWFN'CVX(A)+DTA, FN'CVY(B);
2340 MOVEFN'CVX(A), FN'CVY(B)-DTA: DRAWFN'CVX(A), FN'CVY(B)+DTA
2350 ENDPROC
2360DEF PROCNUMBER :VDU5
2370MOVE FN'CVX('LX)-4*LEN(STF('LX)), FN'CVY('Y0)-20 :PRINT; 'LX
2380MOVEFN'CVX('X0)-150, FN'CVY('LY)+28:PRINT; 'LY
2390IF 'LX>0AND'SX<0AND'LY>0AND'SY<0THEN ENDPROC
2400MOVE FN'CVX('SX), FN'CVY('Y0)-20:PRINT; 'SX
2410MOVEFN'CVX('X0)-150, FN'CVY('SY)+30:PRINT; 'SY:VDU4
2420ENDPROC
2430DEF PROCNAMEY('VNAME$):VDU5
2440FOR 'A=1 TO LEN('VNAME$)
2450MOVE FN'CVX('X0)-60, FN'CVY('LY)-'A*32-32 :PRINTMID$('VNAME$, 'A,1)
2460NEXT 'A:VDU4
2470ENDPROC
2480DEF PROCNAMEX('HNAME$)
2490MOVE FN'CVX('LX)-32*LEN('HNAME$)-64, FN'CVY('Y0)-52 :VDU5:PRINT'HNAME$ :VDU4
2500ENDPROC
2510DEF PROCCIRCLE
2520VDU 20
2530PROCCLARGE
2540FOR TX=0 TO 140
2550HXX(TX)=INT(TX*UB)
2560 IF HXX(TX)*HXX(TX)>RX THEN PRINT TX, SQR(RX), HXX(TX)
2570HYX(TX)=INT(SQR(RX-HXX(TX)*HXX(TX)))
2580DRAW .825*HXX(TX), HYX(TX)
2590NEXT TX
2600MOVE 0, rad
2610FOR TX=0 TO 140
2620DRAW .825*-HXX(TX), HYX(TX)
2630NEXT TX
2640ENDPROC
2650DEF PROCCLARGE
2660INCX=INCX+1
2670rad=(SCF*JKX*10)
2680VDU29, 640, 200;
2690MOVE 0, rad
2700RX=rad*2
2710UB=rad/140
2720VDU4
2730ENDPROC
2740DEFPROCNUMROSE
2750REM *AXIS NUMBERING ROUTINE*
2760VDU5
2770VDU29, 640, 150;
2780 IF CMAX<10 THEN GOTO 2890
2790 CMAX1=INT(CMAX/2)+1
2800 FOR SX=1 TO CMAX1
2810MOVE 0, 0
2820 XRAD=(SCF*SX*16.5)+5
2830 MOVE -XRAD-5, 0
2840PRINT; SX*20
2850MOVE XRAD-10, 0
2860 PRINT; SX*20
2870 NEXT SX
2880 GOTO 2960
2890 FOR SX=1 TO CMAX
2900 XRAD=(SCF*SX*8.25)+5
2910MOVE -XRAD-5, 0
2920 PRINT; SX*10
2930MOVE XRAD-10, 0
2940 PRINT; SX*10
2950 NEXT SX
2960MOVE -4, 0:PRINT"0"
2970 VDU29, 0, 0;
2980 ENDPROC
2990 DEFPROC DUMP1
3000 VDU4:VDU11:VDU13:PRINT"
3010 *GDUMP 0 1 1 1 20
3020 ENDPROC
3030 DEFPROC DUMP2
3040 *GDUMP 0 1 1 1 20
3050 ENDPROC

```

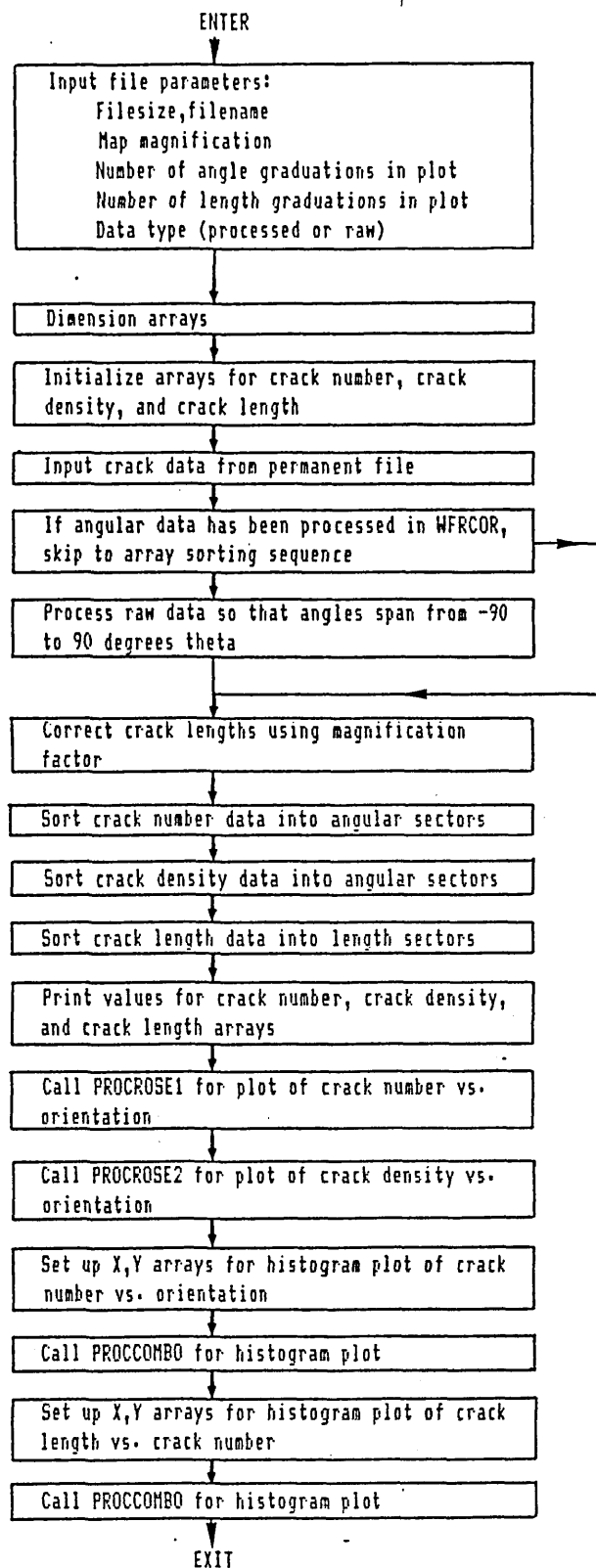


Fig.A-7 Summary flow chart of program HISTPL4.

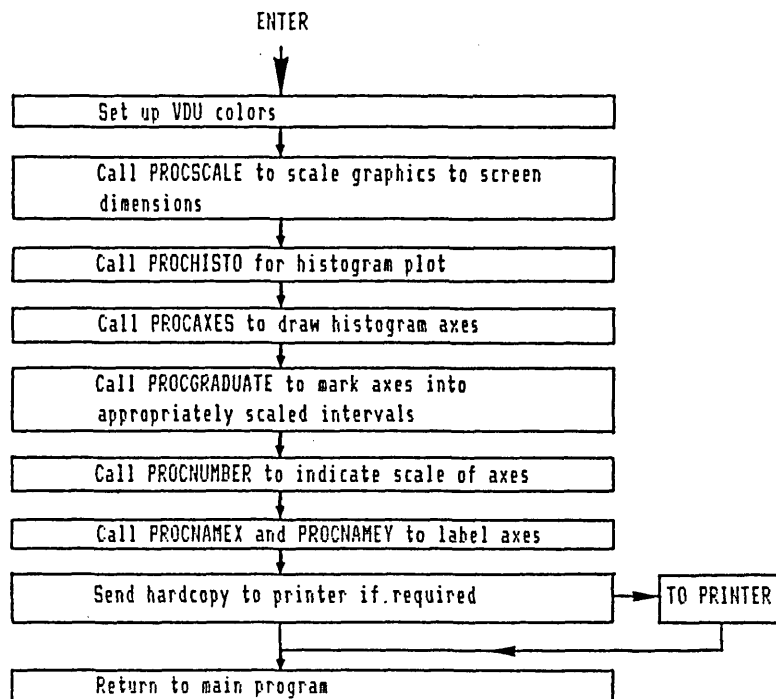
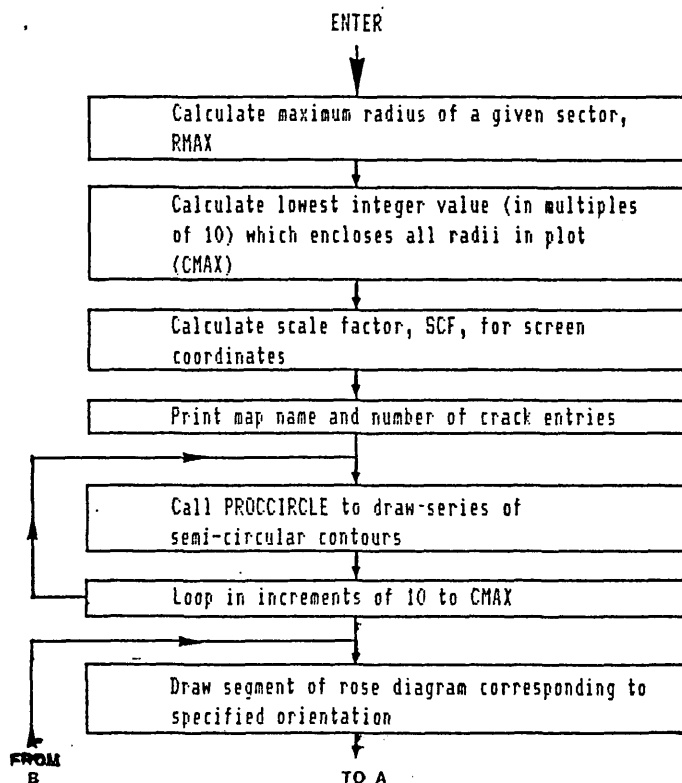
PROCCOMBOPROCROSE1

Fig.A.7 Summary flow chart of Program HISTPL4.

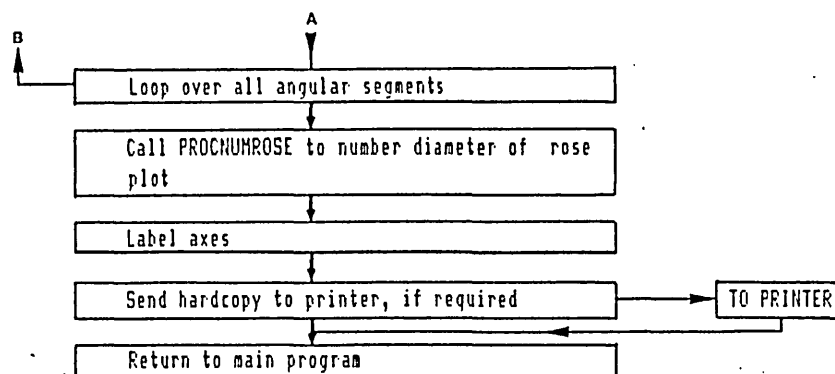
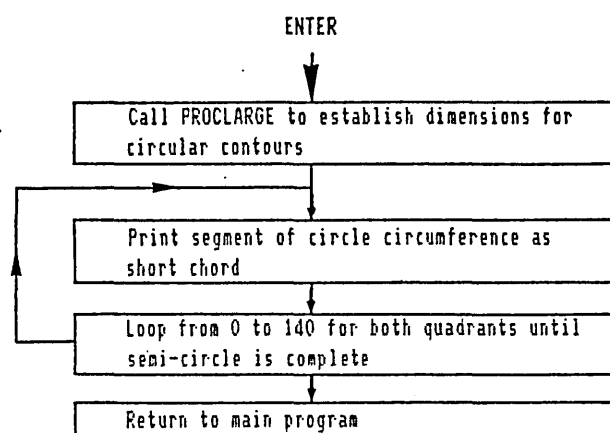
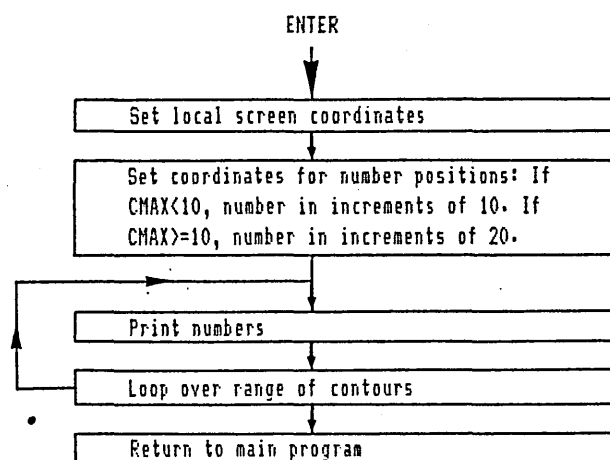
PROCCIRCLEPROCNUMROSE

Fig-A.7 Summary flow chart of Program HISTPL4

Variable Definitions: HISTPL4

Main Program

Array Variables:

AX%	X coordinate of first crack endpoints
AY%	Y coordinate of first crack endpoints
BX%	X coordinate of second crack endpoints
BY%	Y coordinate of second crack endpoints
DENS	Crack density for each angular sector
LGTH	Crack lengths
LGTHSQ	Square of crack lengths, used in calculating densities
SCANL	Number of cracks in each length sector
SCANT	Number of cracks in each angular sector
THETA	Crack orientations
X	X coordinates of histogram plots
Y	Y coordinates (heights) for histogram blocks

Single value variables:

BRACKET	Size of angular sector for orientation data plots
CD	Code variable for separating raw and processed data
FINAME\$	Data file name
FSIZE%	Data file size
GET\$	Printer output control variable
I%	Counter in histogram sorting sequence
J%	Counter in input sequence/histogram sorting sequence
K%	Counter in histogram sorting sequence
LMAX	Greatest crack length value in data file (for sorting)
LTEST	Sector location of individual crack in length array
LTEST%	Truncated value of LTEST
M%	Counter in array initializing sequence
MAG	Map magnification used
N%	Counter in array initializing sequence
NUMLEN	Number of sectors in length data plots
NUMTHE	Number of sectors in orientation data plots
SPACE	Maximum array size for histogram plots
TEMPX%	X storage value for switching AX%,BX%
TEMPY%	Y storage value for switching AY%,BY%
TESTAX	Sector location of individual crack in

Table A.3 Variable Descriptions: Program HISTPL4

	orientation arrays
TTL	Cumulative squared crack length
UX	Axis labeling control variable
WINDOW	Size of length sector for length data plot
Z	Permanent file value in output sequence

Variables in rose diagram procedures

Array variables:

HX%	X coordinate for chord endpoints in circle plots
HY%	Y coordinate for chord endpoints in circle plots

Single value variables:

CMAx	Maximum number of contours for plots with <100 cracks in single sector
CMAx1	Maximum number of contours for plots with >= 100 cracks in single sector
INC%	Counter in contour plotting sequence
JK%	"
KL%	Counter in plot scaling sequence
L%	Counter in rose diagram plotting sequence
PHI	Width of angular sector
R%	Square of circle radius in contour plotting sequence
rad	Circle radius in contour plotting sequence
RMAx	Maximum number of cracks in single angular sector
S%	Counter in diagram numbering procedure
SCF	Scaling function
T%	Counter in contour plotting sequence
XRAD	Position (screen coordinates) of contours along semi-circle diameter
UB	Real value of X coordinates of chord endpoints in contour plots