ICE PETROFABRICS, TUKTOYAKTUK, N.W.T., CANADA

by

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ABSTRACT

This thesis attempts to elucidate the origin and deformation of a folded sequence of ice and icy sediment in Tuktoyaktuk, N.W.T., Canada. Tuktoyaktuk lies between the maximum and late Wisconsin limits of glaciation.

Bodies of underground ice in permafrost have characteristic ice crystal sizes and shapes and inclusions dependent on the mode of ice growth and subsequent deformational or other history. The ice body which was studied lies beneath 2 m of fluvioglacial sands and 0.6 m of gravel. The ice-icy sediment foliation has been deformed into subhorizontal isoclinal folds, the major movement being from the SSW. Folds are classified into three styles. Fabric diagrams of ice crystal optic axes are of two types. A relict early fold shows a cleft girdle pattern at right-angles to the fold axis. Later flattening and fold limb extension has given rise to fabric diagrams with strong maxima normal to the axial surfaces, showing that crystals have rotated such that slip planes are parallel to the surface of slip of the body. Differences in deformabilities of pure ice and ice with varying amounts of sand have given rise to boudinage and transposition-type structures. Four types of grain texture indicative of recrystallization and dependence on sediment, are distinguished.

It is not possible, with the available evidence, to distinguish between two alternative origins of the body as segregated ground ice overridden by an ice-sheet or a remnant of a deformed ice-sheet terminus. Necessary conditions for the survival of either body may be inferred. Petrographic characteristics are listed for future field recognition of the ice type.

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CHAPTER I

INTRODUCTION AND STATEMENT OF THE PROBLEM

General Statement

Permafrost underlies approximately one half of the land area of Canada (Brown 1967, p. 741). Within such a zone, bodies of underground ice may exist in a variety of forms (Mackay 1972a, p. 5), ranging from hairline lenses to bodies of massive ice at least 35 m thick (Mackay 1971, p. 397). Ice thus has a great areal distribution, it being estimated that ice-wedges alone are found in perhaps 2,600,000 km^2 of the northern hemisphere (Mackay 1972a, p. 5); further, drill hole records show the existence of alternating ice and sediment layers at depth.

It is evident that a knowledge of underground ice characteristics is important for an understanding of the past, present and future geomorphic development of regions containing permafrost, and of the probable effects of proposed human activities.

A review of the literature shows that geomorphological investigations in Canada have been confined largely to studies of surface expression. Studies of subsurface structure in the field area have been limited to drilling of pingos, inspection of slump faces, probing of ice wedges, and analysis

of drillhole records not prepared for that purpose. Elsewhere detailed studies on several ground ice types have been carried out (Black 1953, Corte 1965). Where exposure in the third dimension is available, it is clear that the morphology of the ground surface may give no indication of the presence of, say, wedges. Mackay (1972a, p. 5) points out that "Some (forms) are distinct and easy to recognize, whereas others are transitional and impossible to identify". On this point, it is noted that the exact distribution of ice bodies is only poorly known, based on aerial photograph inspection, a study of shot hole logs and limited field mapping. At this macroscopic scale, a mapping project to ascertain the occurrence of various ice types from sample locations would benefit greatly from a knowledge of the characteristics of the ices which are readily recognizable in the field. Where it is impossible to forward frozen specimens for laboratory analysis, features such as grain size, grain shape, sediment and gas content and their directional structures relative to local ground surface are vital parameters for their accurate recognition.

This is true not only for the preparation of maps of various scales, but also for local knowledge of subsurface properties of the ground, necessary in any considerations of engineering or general construction schemes.

Considering the development of a given icy body, growth occurs by accretion of layers of crystals, as in the infilling

of open ice wedges, or during the penetration of a freezing front into sediment where water is available for freezing. "Individual increments of ice average 2 mm per cycle" in the case of ice wedges (Brown 1966, p. 1) but a wedge does not crack every year, and individuals grow at different rates. The rates quoted by Brown are considered high for the Mackenzie Delta area (Mackay, personal communication). With this average of less than 2 mm in mind, it is evident that investigation must be made at this scale to be useful. Further solid, liquid and gaseous inclusions are of this size, and their positions relative to crystals are meaningful in terms of growth history.

In this area, ice bodies of several ages are known. Also, in the outer islands of the Mackenzie Delta are exposed masses of underground ice which have been deformed by glacier ice-thrust. The possibility that remnants of the ice-sheet responsible for that deformation exist buried in the area has not been ruled out. Thus within the field area, there may occur ices of several origins and subsequent histories.

As an example of the need for criteria by which to distinguish ice bodies, an ice cellar in the settlement of Tuktoyaktuk, N.W.T. was chosen for a detailed study of mesoscopic and microscopic form. In addition to the geocryological attributes, the particular cellar was chosen for logistic reasons: (a) ease of access in all weathers and (b) local electricity supply for equipment.

Statement of the Problem

In the Tuktoyaktuk ice-cellar alternating ice and icy sediment bands display isoclinal folds with sub-horizontal axial surfaces and other evidence of strong deformation (Plate 1). Thus both the original ice growth and the stress system responsible for its subsequent deformation are of interest.

The objectives of this paper are:

(1) to elucidate the mechanism of ice growth and incorporation of sediment

(2) to decipher the mode of deformation of the sediment-ice system

(3) to infer the post-deformational history of the body, its stratigraphic position, and the temperature requirements for its continued existence

(4) to ascertain distinctive features of the ice body for future field recognition from limited samples.

General approach

In order to determine the deformational history of a body of folded ice and sediment, it is necessary to determine as completely as possible the present configuration of all geometric features, i.e., the fabric of the body. Then, assuming an original configuration of these features, a sequence of movements must be proposed which lead from the original to the observed geometry. The assumption is made that the original layering was sub-horizontal. This is

reasonable, due to the presence of sedimentary structures within the beds.

For any original and final configurations there is an infinite number of strain paths which could lead to the observed structures. The practice here is to take the simplest as most likely. Also the mechanism of deformation must be mechanically and glaciologically feasible. The principle of symmetry places a limitation on the interpretation of movements.

Considering the alternate ice-icy sediment layering, a means of inclusion of sediment within ice must be proposed. The subsequent deformation of the body is recorded in the fold morphology and micro-fabric. In order to understand the meaning of the characteristic fold forms and microscopic features, knowledge is required of the deformational characteristics of ice and icy sediment. Thus review is made firstly of known mechanisms of incorporation of sediment within ice, and secondly of laboratory and field studies of ice deformation.

Organization of Thesis

The remainder of the thesis comprises an introduction to the field area, followed by:-

(a) Chapter II - a literature review of the mechanisms of ice growth in sediment with and without external overburden and the entrainment of sediment in glacier ice.

(b) Chapter III - a literature review of deformation of ice and the sand-ice system in laboratory experiments, and the application of these results to the field situation.

(c) Chapter IV - a discussion of the methods of mesoscopic fold analysis; the methods of ice petrofabrics, including studies of optic axis orientation, grain size, shape, distribution of inclusions of gas and sediment, and their interrelations.

(d) Chapter V - results
- (i) mesoscopic structures
- (ii) microscopic structures
- (iii) optic axis orientation
- (iv) grain shape
- (v) grain size
- (vi) sediment distribution and size, effect on ice characteristics
- (vii) water quality analysis

(e) Chapter VI - Conclusion

THE FIELD AREA

Field work was undertaken in the vicinity of Tuktoyaktuk ($69^{\circ}27'$ N; $133^{\circ}00'$ W), N.W.T. (Fig. 1), and shown on map sheet 107C. The geographical nature of the surrounding land area was described by Mackay (1963) and Bouchard and Rampton (1971); some submarine features have been discussed by Shearer et al

(1971) and Mackay (1972).

Tuktoyaktuk is sited on the Pleistocene Coastal Plain, in an area of "Undifferentiated Coastlands" (Mackay 1963, p. 137). The coastlands in general have over 15% of the surface lake-covered, this figure rising to over 50% around Tuktoyaktuk. There also are channels tending to produce an indented coastline, as at Tuktoyaktuk harbour, although spit growth causes some smoothing-off. Coastal recession is occurring, causing drainage of lakes, in which pingos may grow. Another major feature is the involuted hill, occurring to the east and southwest of the field region. These hills have relief of 100 to 150 feet, rising in a stepped manner, there occurring ridges on step edges. Where slumping produces an exposure, extensive ground ice is seen, overlain by till-like material in which ice wedges have grown.

The Quaternary history of the region has been discussed by Mackay (1963), Mackay and Stager (1966), Mackay et al (1972), Rampton (1970, 1971, 1972a, b) and Rampton and Mackay (1971). In summary, it may be stated that the majority of the coastal plain lies within the inferred limits of continental glaciation. Available radiocarbon dates (Mackay et al 1972, p. 1321) indicate that the northern limit of the "classical" Wisconsin ice lies south of a line Richards Island--northern Tuktoyaktuk peninsula, and north of Sitidgi Lake. Mackay et al (1972, Fig. 1) place the limit approximately mid-way between Sitidgi Lake and the settlement of Tuktoyaktuk (Fig. 2).

Thus, the characteristic features are not direct results of glaciation, but lakes, for example, are of thermokarst origin; positive relief features mainly result from various ice-growth processes, discussed later.

The surficial geology of the Tuktoyaktuk area comprises fine to medium grained Pleistocene sands, in thicknesses of 100 feet and more, capped in places by a clayey diamicton up to 25 feet thick (Rampton and Mackay 1971, p. 5). This diamicton varies with locality from till to mudflow or pond-deposit.

Several types of massive ice and icy sediments in this region have been noted by Rampton and Mackay (1971): pingo core ice, massive ice in a coastal slump, alternating ice and icy sediment in an underground cellar. Additional ice-types have been described by Mackay (1972a) as: - tension crack ice, aggradational ice and sill ice. Also the possibility of buried glacier ice has not been discounted (Mackay 1972a, p. 5). Glacial deformation of massive ground ice has been discussed by Mackay (1956, 1959, 1963, 1971); Mackay and Stager (1966); Fyles (1966); Kerfoot (1969), in the coastal area between Herschel Island and Nicholson Peninsula.

CHAPTER II

ICE GROWTH IN SEDIMENT AND THE ENTRAINMENT OF SEDIMENT IN GLACIER ICE - A LITERATURE REVIEW

Introduction

The ice body under consideration displays alternating layers of ice and icy sediment. It is thus necessary to explain the variation in sediment content and the particular grain size in a given band. The mesoscopic fold form suggested, on the first examination, a strong similarity to folds described from terminal regions of present-day ice sheets. Also the Tuktoyaktuk area has been glaciated and the suggestion has been made that glacier remnants may underlie parts of the area. Massive beds of segregated ice deformed by over-riding ice sheets are known in the area. Thus an important aspect of this study is to attempt to distinguish among possible origins of the Tuktoyaktuk ice, namely:

(a) formation as part of an ice sheet,

(b) segregated ice which was later deformed, and

(c) other.

The present fabric is a function of the original fabric, thus discussion is made of possible pre-deformational geometries.

Ice-Growth in Sediment

The origin of ice layers and cement in sediment has been discussed by Williams (1967) and application of theories to the field situation in permafrost areas of Western Arctic Canada has been made by Mackay (1971). A distinction is made between freezing of a previously unconsolidated sediment by downward penetration of a freezing front, from the ground surface, and the freezing at the base of an ice sheet, i.e., beneath an overburden other than the soil and ground ice.

Freezing Without Overburden

In unconsolidated sediment, segregated ice forms when pore water pressure is high, pore ice when it is low. We have

p_i = pressure of the ice

p_w = water pressure

σ_{iw} = ice-water surface tension

r = radius of soil pore to permit advance of frost line

When $p_i - p_w < \frac{2\sigma_{iw}}{r}$ segregation ice

$p_i - p_w > \frac{2\sigma_{iw}}{r}$ pore ice

Variations in water supply, soil water movement and heat extraction give rise to alternations between the two types (Williams 1967, Mackay 1972a, p. 17).

Discussion has usually considered the downward penetration of a freezing front; however lateral and upward shifts are possible, as from the base of the active layer in winter, and into a slip face.

Williams (1967, p. 96) also examined the influence of air on freezing in unsaturated soils, whereby permeability is reduced and pore-water pressure is affected. Observation of segregation ice indicates gas bubbles to be present. Mackay and Stager (1966) noted elongated bubbles aligned normal to the layering of ice lenses. Elsewhere spherical bubbles occur.

Fabric of Segregated Ice

The ice grain fabric in segregated ice is a function of nucleation and epitaxial growth. At the initial stage of ice crystallization in sediment, random nuclei form. Some grow rapidly to critical size and survive; others redissolve. Of the survivors, those with c-axes oriented parallel to the direction of heat flow grow most readily. In the case of a downward penetrating freezing front, a vertical preferred orientation would be expected.

Incorporation of Sediment Into Ice Sheets

Weertman (1957, 1964) developed a model for the movement of glaciers over obstructions through two processes: (a) stress concentration on the up-glacier side leading to

greater strain rates and thus accelerated plastic flow, and (b) ice melting on the high pressure side and refreezing on the low pressure side. Kamb and LaChapelle (1964) observed sliding at the base of Blue Glacier, and described a clear, bubble-free ice layer up to 3 cm thick, distinguishable by texture and structure from the overlying ice, which they referred to as regelation ice. On the basis of observations and experiments, Kamb and LaChapelle concluded that plastic flow due to stress concentrations is of little importance. Further Barnes and Tabor (1966) investigated the hardness of ice; with specially prepared bubbly ice, the ice in the zone affected by pressure became transparent in comparison to the surrounding bubbly ice, supporting Kamb and LaChapelle's suggestion. It is apparent that regelation is essential to basal sliding (in the absence of surging).

Two major hypotheses have been propounded for the incorporation of englacial material.

The Shear Hypothesis

The suggestion is that shearing occurs and material is transported along discrete failure surfaces. Material is assumed to be scraped into shear surfaces by differential ice movements. However, from descriptions of debris bands--dense layers of sand and boulders 0.5 m thick, and layers of finely disseminated sediment particles 1 to 2 m thick, the suggested mode of incorporation seems unlikely. Further,

Goldthwait (1951 p. 569) described "shear planes" in the Barnes Ice Cap which curved around boulders and till clots, forming augen-like structures. Plastic deformation is more acceptable than brittle failure as an explanation of the latter feature. Recently Gow (1972) reported similar structures in the Garwood Glacier, Antarctica.

Weertman's Theory

Weertman (1961 p. 968) discounted the shear hypothesis on several grounds, including that of the close proximity of debris layers. If the sediment horizons are of shear origin, then closely-spaced shear surfaces must exist. Simple tectonic theory precludes this. There is no reason why yield should cease along one plane of weakness and a new plane form less than 1 cm away. Further, investigations of movement along debris surfaces exposed on tunnel sides have provided no evidence of discrete shears. Butkovitch and Landauer (1960) recorded no shearing motion across debris layers, although differential flow occurred in the ice. Abel (in Swinzow 1962, p. 223) found that bands of debris gave increased differential flow.

Weertman (1961, p. 270) proposed a freezing model to explain Thule-Baffin moraines, arguing that water produced by melting in inland parts of an ice sheet moves down the pressure gradient to a region where the temperature gradient in the ice can conduct away more heat than is produced by

sliding or comes from geothermal heat. Water is considered to refreeze onto the ice sheet.

According to this theory, a shift in the amount of heat produced due to sliding will lead to a freezing-in of debris, as the 0°C surface passes down. Repetition of the cycle leads to multiple layers. However, this necessitates frequent shifts in the position of the melting point isotherm; such rapid changes in the thermal regime of the basal region are unlikely. Further, Williams (1967, p. 108) points out that, due to overburden pressure of an ice mass, sediment below an ice sheet cannot have ice in its pores, unless there is an associated increase of ice thickness.

Other theories

A later theory by Boulton (1970) has as its basis the freezing-on mechanism, in this case the source of sediment being an actively eroded rock projection where particles freeze with regelation ice, the bands so formed being subsequently folded. Souchez (1967) had previously alluded to this process in a study of Victoria Land, but in that case no folding occurred. Souchez described the glacier bed as consisting of rock fragments of different sizes, ranging from silt to blocks and slabs (1967, p. 841). Thus a grain-size selective process was necessary to explain the 12 mm diameter size in debris bands. He suggests that the

regelation process accounts for this. A second type of debris band, cutting, and thus younger than the first, was described by Souchez as oblique to the glacier margin, and containing coarse material, but no fines. Hooke (1969) reported that in his Greenland studies, debris layers were seen to contain all sizes of material and fluvial stratification was retained in some cases--such would not be preserved if blocks were "sheared" into the ice. Further, Hooke (1969, p. 351) suggested that the secondary bands mentioned by Souchez were in fact crevasses infilled from above.

Thus there occurs in the literature disagreement concerning the origin of sediment in present-day ice sheet and glacier bases. What is agreed is that sediment, usually fines, occurs, that bands may become highly folded, and shears may be present.

A recent note by Gow (1972) contains a description of alternating laminations of sand and dust, and dirt-free ice in Antarctica. The debris was considered to be of periodic deposition derived by wind from sources of exposed rock and volcanic ash. Gow (1972, p. 101) also referred to thick sand and gravel sequences, which were highly folded (Gow, Fig. 2) but still exhibit size sorting, cross-bedding and lensing--characteristics of water deposition. Gow argued that the level of occurrence in the ice precluded origin at the glacier bed, but favoured deposition at the top of the glacier.

Considering the first suggestion of wind-transport, little mention has been made of this by other authors. Goldthwait (1960) recorded that only 0.1% of sediment transport around the ice-cliff at Nunatarrsuaq (Greenland) was by wind. No suggestion was made of incorporation of such material into the ice sheet there. In agreement with the case of fluvial transport of material, Nichols (1964) reported undeformed interbedded layers of fluviatile cross-bedded sand and gravel less than 0.5 m thick deposited in summer on the previous winter's snow accumulation.

During the course of a long-term detailed study of a present-day ice-sheet terminus, Goldthwait (1960) considered the origin and folding of dirt bands. Observations over several years in artificial tunnels, subglacial caverns and stream routes indicated that "some or all of the dirt now circulating near the ice front is simply reincorporated in the basal layers of ice as the white ice of the glacier above advances onto its nearly stagnant dirt-covered toe ice" (Goldthwait 1960, p. 71). A stream section exhibited the successive incorporation of this superimposed ice and dirt into the body, yearly accumulations being identified by "deadmen" stakes. Thus a cyclical process was envisaged, whereby sediment became included into the ice, then folded and sheared, moving progressively to the cliff face to fall to the toe and restart the cycle. According to Goldthwait the cycle might take as little as 25 years or as much as

12 centuries.

The existence of isoclinal folds in the terminal region was noted by Goldthwait (1960, p. 68) and by Merrill (1957) to occur on several scales. Studies of the motion of the cliff revealed that the upper part moved twice as fast as the lower, shearing motion being largely concentrated at the base of a vertical cliff. Despite strong shearing, the ice surrounding the rocks on the glacier bed had not moved in less than 200 years, as moss, lichen and vascular plants of that age were perfectly preserved.

While one layer becomes folded within the actively deforming ice subsequent layers are added below. Thus all stages of foliation geometry would be expected at a given time, from sub-planar beds through open folds to more tightly appressed limbs. This could occur while the ice sheet was stationary or moving (Boulton 1970).

Fabric of undeformed basal ice

In the studies reviewed above, no consideration was given to ice textures. Kamb and LaChapelle (1964) mentioned that regelation ice was distinguishable from overlying ice by structure and texture, but did not say how. Other workers ignored the topic. By analogy with segregation ice growth it is suggested that, as a body of ice is present as a nucleus, new grains will grow with c-axes approximately parallel to the direction of local heat flow. This assumes the absence

of stress. Under active stress basal planes would be orientated to accommodate that stress.

Conclusion

Several mechanisms have been propounded to account for the presence of extended sediment layers in undeformed and in deformed ice. In the case of rhythmic ice banding in soils, alternate bands of high ice content and high sediment content result from local variations in ice nucleation and growth, the availability of water and its flow to the freezing front, and the removal of heat. Such a theory would explain the vertical changes in sediment content in the predeformational state of the Tuktoyaktuk ice. Lateral changes in bed thickness would also be expected. In this case the sediment size would be a function of pre-freezing deposition. The freezing process would not be grain-size selective, although sandy layers would be separated by ice lenses along silty laminae.

Considering sediment entrainment in ice sheets, several theories have been advanced. The shear hypothesis is discounted, as shears separated by only a few centimeters are unlikely, but this does not mean that shears do not occur. Freezing-on of fine-grained sediment at glacier bases has been described from areas with different sized fragments at the bed. Thus a grain-size selective process is possible. In this case water-quality would be expected to be similar to that of local ground water, in contrast to water chemistry in ice

at upper levels on the same glacier where fine grained material could be of wind-blown origin.

Thus in addition to the pattern of sediment in the ice, consideration must be given to grain size, to determine its mode of transport, and water quality in comparison to characteristic properties of ice of known glacier origin, and other ice bodies in the Tuktoyaktuk area.

CHAPTER III

DEFORMATION OF ICE AND THE SAND-ICE SYSTEM

Introduction

The ice body beneath Tuktoyaktuk contains layers of ice with dispersed sediment, and other layers with high sediment content. These bands vary in thickness and in lateral extent in their present state, and in some cases 2 or more layers merge into one. Under conditions of deformation the several types of material would be expected to behave differently. As pressure and temperature fluctuated so would the relative "competences" change. The original pre-deformational foliation is assumed as sub-parallel ice and icy sediment bands. The foliation attitude is considered to have been sub-horizontal, evidence being the orientation of retained sedimentary structures relative to the prevailing foliation.

A deformational path from the original geometry to the presently observed fabric must be proposed. The deformation mechanisms must be not only geometrically realistic, but also glaciologically feasible. Thus consideration must be given to the known properties of ice under varying conditions of loading. Sediment occurs in some of the ice, thus the relative deformabilities of sediment-free and sediment-rich ice must be investigated. The deformation ceased thousands of years

ago, thus post-deformational processes in ice require investigation, and means of recognition of associated properties enumerated.

Chapter Outline

It is thus necessary to consider the reported results of laboratory and field studies on ice deformation. Discussion is introduced by a literature review of single-crystal response to loading. This is followed by a summary of the deformation properties of pure ice crystal aggregates under conditions of tension, compression and shearing for varying stresses, times and temperatures. The microscopic features indicative of such deformation are discussed, based on Gold's work (Gold 1963). Investigation is then made of the additional effect of included sediment in varying proportions.

Review of Experimental Deformation of Ice

For a study of a deformed body such as is under consideration, knowledge is required of the deformational characteristics of pure ice and ice containing various proportions of sediment. Investigators have studied both actively deforming glaciers and prepared samples in the laboratory. This review will discuss the results of controlled experiments, separate consideration being given to deformational properties of single crystals and of polycrystalline ice.

(a) Single Crystals

McConnell (1891) established that single crystals deform plastically by glide on the basal plane. The majority of evidence indicates that this is the only effective slip surface (Glen and Perutz 1954; Steinemann 1954; Kamb 1961); however, Muguruma et al (1966) reported non-basal glide, requiring a stress 20 times greater than for basal glide.

Considering the basal slip planes, Nakaya (1958) demonstrated that slip bands are concentrated into a series of zones approximately 0.06 mm apart and parallel to the basal plane. Previously Steinemann (1954) had found no direction of easiest glide within the glide plane. Other workers (Griggs and Coles (1954); Steinemann (1954); Jellinek and Brill (1956)) concluded from measurements of single crystal creep that for a given stress, the rate of strain increases with time, and the ice is said to be softened.

(b) Polycrystalline Ice

On the basis of single crystal results it follows that in a polycrystalline aggregate where individual grain orientation is random (in the present argument) material continuity demands that other mechanisms operate to permit contiguous grains to conform to arbitrary shape changes. Grain boundaries introduce constraints to dislocation within a given grain. If grain integrity is to be preserved, each must deform in a manner compatible with its immediate neighbours.

Grain orientation determines the constraint, thus the observed deformation in polycrystalline ice results from individual grains attempting to deform singly, but being compromised by others. Analogies between single crystal deformation and polycrystalline behaviour are not of great value. Laboratory observations on ice creep have shown a dependence on stress orientation, temperature, time and impurities.

(i) Stress Orientation

In an early study, Bader et al (1939) deformed ice blocks, then measured the orientation of up to 40 grains per sample. (For comments on validity of such sample size, see Chapter IV). Samples were deformed: (a) in compression; (b) in tension; and (c) in shear. A compressed sample showed preferred orientation with all 26 grains within a girdle 20° to 45° from the unique stress. Deformation in tension of another sample for 49 days led to axial groupings within 45° of the inferred tensional axis. Shearing of a specimen for 6 days at 4 kg cm^{-2} produced an axial distribution diagram showing 4 preferred directions, 2 in the plane containing the shear. The authors concluded that the translation plane for ice in compression is normal to the stress axis, in tension it is parallel to the tension axis, and in shear parallel to the shear plane. Considering crystal orientation, Steinemann (1958, p. 48) found a fabric similar to that of Bader for a sample in compression, most axes being 20° to 50° from the

unique axis. Stanley (1965) experimented with ice in compression, and produced diagrams for specimens recrystallized under stress, showing maxima in a 30°- 50° small circle centred on the stress axis, with maxima of 3 to 5%. Stanley argued that inclinations of 45° to the stress axis would result if grains crystallized with basal planes paralleling the plane of maximum shear stress, but found that in practice, planes of failure are at less than the 45° angle predicted. Were basal planes parallel to such failure surfaces, the c-axes should be at inclinations of 45° to 75° from the stress axis. Stanley (1965, p. 158) explained the c-axis inclination by assuming the basal planes to be subparallel to surfaces of rheid flow. For ice recrystallized in tension experiments, c-axes tend to be inclined at high angles to the tension axis. However, few fabrics have been determined for this condition. Bader et al (1939) made the first attempt at correlation between stress and orientation of ice crystals, and indicated crystal growth occurred in ice under shear. Perutz (1940, p. 133) stated that an increase in grain size is the inevitable result of strain, thus corroborating the observations of Bader et al. The experiments of Steinemann (1958) indicated the occurrence of "primary parakinematic recrystallization", i.e., an increase in grain size during load, in addition to the normal increase in size on load release ("postkinematic recrystallization").

The above agreement on the role of stress in crystal growth is not ubiquitous in the literature. In the experiments

of Shumskii (1958, p. 246), recrystallization under stress resulted in a reduction of average grain size. From work on the Blue Glacier, Kamb (1959) related fine layers to high stress zones, and coarse layers to zones of very weak stress. Further, Glen (1958) and Seligman (1949) suggested a close relationship between small grains and high stress.

(ii) Temperature

The disagreements in observations are probably related to the ice temperature during deformation. Near 0°C, ice recrystallizes so that a rapid increase in grain size occurs (Rigsby 1960, p. 606). It is noted that the experiments reported above in which applied stress resulted in grain size increase, were not temperature controlled. In the work of Bader et al (1939, p. 53) the ice was subjected to average stresses of 4.5 kg cm^{-2} at cold room temperatures of -4°C to -5°C. It may be argued that temperature was of more importance than stress.

Rigsby (1960, p. 604) found that "Recrystallization after deformation is much retarded at lower temperatures, and is extremely slow below about -5°C. Below about -10°C, recrystallization appears to have almost stopped". However, these experiments were of short duration--extrapolation to the geological time scale is not necessarily justified.

(iii) Stress-release

Considering the role of stress-release in crystal growth, Seligman (1950) reported an 8-fold increase in crystal size in ice blocks removed from a glacier tunnel ice-face and left to stand. Although suggesting stress release to be the dominant mechanism, he did not rule out the possibility that the temperature factor contributed in the form of air circulation.

In an experimental attempt to establish a relationship between grain size and stress release, Glen (1955) subjected ice thin sections to stresses, and found that under 8.5 kg cm^{-2} stress smaller crystals resulted than under 3.6 kg cm^{-2}. Ice subjected to 5 kg cm^{-2} recrystallized in the section, indicating the trapping of large stresses.

(iv) Hydrostatic Stress

Rigsby (1958) concluded that temperature is far more important than hydrostatic pressure in both regulation of deformation rate, and rate of recrystallization. Glen (1958, p. 261) reports the unpublished work of Steinemann who studied the effect of hydrostatic pressures up to 80 kg cm^{-2} on the rate of shear strain of ring-shaped specimens. No definite effect was found; this, in conjunction with Rigsby's experiments for single crystals, is evidence that hydrostatic pressure has no direct effect on the plastic properties of ice.

(v) Time

The importance of the time factor in the strain and growth of ice is poorly understood. A proposal by Demorest (in Knopf, 1953) that crystal deformation leads to an unstable lattice which recrystallizes instantaneously was refuted by Glen (in Knopf 1953, p. 219). The conditions assumed by Demorest lead to a definite but sometimes slow growth rate. Knopf claimed that recrystallization occurred within "a few minutes" in ice near the melting point; hence again the role of temperature is indicated.

(c) Microscopic features indicative of Deformation

As discussed earlier single crystals of ice deform by slip on the basal planes of the lattice. At grain contacts (i.e., boundaries) changes occur, grains rigidly slipping past one another, independently of translation gliding which may or may not be occurring within a given grain. Little movement can occur on grain boundaries before irregularities on the boundary prevent movement, thus strain accumulates within the grains. In this case, the probability of recrystallization, i.e., of both the nucleation of new grains and their subsequent growth, increases as the internal stress builds up. The new recrystallized material which will appear continually will be free from internal strain at the instant of formation. Glen (1955) suggested that the mechanisms of grain boundary migration and recrystallization allow grains to conform to

the imposed deformation.

Gold (1963) observed and described deformation mechanisms in ice under a compressive load. The mechanisms are enumerated below, in chronological order of occurrence.

(i) Slip bands

Slip occurs when one part of a crystal slides over another part without loss of cohesion, the lattice orientation in each part being similarly orientated before and after the movement. In ice the slip bands are parallel to the basal plane, and thus at right angles to the optic axis. More work has been done on metals than on ice. Gold draws an analogy with hexagonal metals.

(ii) Grain boundary migration

Grain boundary migration is one of the first signs of change in the grain boundary configuration, occurring in "practically every boundary" (Gold 1963, p. 13). In a discussion of rock deformation, Flinn (1965) distinguishes between such migration at low and high temperatures. Atomic transfer from a relatively strained grain or part of a grain on one side of a boundary to a relatively unstrained grain or part of a grain, on the other side, occurs at low temperatures. Thus unstrained material is built up at the expense of strained lattice, resulting in sutured grain boundaries (Fig. 18 and 22) which are common in quartzites. MacGregor (1951, 1952) discussed the similarity between ice and quartz deformation.

At higher temperatures, a tendency for grains to minimize their area occurs, boundaries migrating toward their centres of curvature, resulting in equiangular aggregates of equiaxial grains. Sections of such material show networks of nearly straight grain boundaries meeting in triple points. Such networks were shown by Voll (1960, p. 529) to be characteristic of monomineralic rocks.

(iii) Kink-Bands

The formation of kink-bands, which have been reported in metals, especially of hexagonal symmetry (Hauser et al 1955) is a mechanism by which a bending moment, transverse to the slip direction, can be relieved in crystals with only one or two possible slip directions (Fig. 3).

(iv) Distortion of Grain Boundaries

Increased deformation in Gold's compressive tests led to distorted grain boundaries. When the slip planes of adjacent grains were suitably oriented, the boundary developed a stepped appearance. With other orientations, small cracks appeared. Such distortions would disappear during recrystallization.

(v) Crack Formation

Gold (1960) showed that cracks may be intercrystalline or transcrystalline, that they propagate in the direction of

the grain long axis, and their plane parallels the stress direction. Gold (1963) summarized other literature, stating that dislocations associated with creep are blocked, cracks nucleating at concentrations of such dislocations which cause local stress exceeding the material strength.

(vi) Cavities

Cavities were observed in regions of grain boundaries, boundary triple points, and intersections of slip planes and sub-boundaries, later becoming infilled.

(vii) Recovery and Recrystallization

A distinction is made between these two processes. Recovery is where dislocations within grains migrate by diffusion into arrays of lower free energy. Dislocations accumulating as a network of sub-boundaries leads to polygonization (Cahn 1949). Elimination of strain from the grains by recovery and grain boundary migration may be of sufficient magnitude to preclude subsequent recrystallization by nucleation and grain growth.

Recrystallization is the solid state process whereby new crystals nucleate, activated by strain energy. Nuclei with mobile boundaries may grow through old strained grains. The new grains are characteristically strain-free and thus may be distinguished from relict grains. If sufficient strain energy is available the process may continue until the new

grains meet; otherwise remnants of old strained grains are found.

In the experiments of Gold (1963), no surface evidence of recrystallization during deformation was observed, but after removal of the compressive load, both recovery and recrystallization occurred at the surface and internally. Gold produced photographic evidence of irregular grain boundaries and associated polygonization, and of a sub-boundary terminating at a slip plane. A comparison of thin sections showed a tendency for columnar grain structure to be transformed into a granular one.

Further, Steinemann (1958) showed that if thin sections are cut immediately after experiments and others later, then complex intergrowths have vanished in the latter, but the shape of grains is far from isometric. In his study it was noted that deformation in tension and compression gave the same results.

(d) Application to Field Situation

The studies reported above have been confined to conditions of laboratory deformation. Recognition of microscopic features characteristic of the several stages of deformation and post-deformational recovery and recrystallization is important for an understanding of the history of the ice at Tuktoyaktuk. Thus consideration is given to petrofabric indicators of deformation.

Accommodation to the imposed stress should result in both preferred optic axis orientation and preferred dimensional orientation. There are several stress-controlled mechanisms productive of preferred lattice (optic) orientations. During gliding, ice crystals rotate until the single slip planes are parallel to each other and perpendicular to the principal stress axis in non-rotational strain, or parallel to the movement surface in simple shear. During recrystallization, preferred lattice orientations may be produced by:

(a) an increased proportion of crystals with favourable orientations to accommodate to imposed stress

(b) a reduced proportion of crystals with unfavourable orientations.

(c) changing orientations from unfavourable to favourable.

Stanley (1965, p. 164) argued that if "unfavourable grains are eliminated, and their ions "transferred" to other grains, favourably oriented grains should become progressively larger". However, he goes on to point out that ice movement is probably one of continual recrystallization. Shumskii (1958) proposed that the least stressed grains replace the more highly stressed crystals which disintegrate by a process of polygonization, or by migratory recrystallization.

The nucleation and orientation of crystals in stress fields has been given theoretical consideration by Kamb (1959), Brace (1960) and MacDonald (1960). Both Kamb (1959a, p. 160) and Brace (1960, p. 15) have noted the similarity between

preferred orientations expected to result from different mechanisms. The total energy of polycrystalline aggregates with an appropriate preferred orientation is lower than that of a random aggregate. The mechanisms which may give rise to a thermodynamically stable orientation are grain boundary migration eliminating grains in an unfavourable orientation, and nucleation creating new grains in a thermodynamically favourable attitude. Elastic straining is necessary for the processes to occur (Flinn 1965).

For ice in shear, Rigsby (1960, p. 603) obtained a fabric with a weak maximum in the theoretically predicted position; most other investigators report fabrics displaying two or more maxima inclined from the pole to the shear plane. Reid (1965, p. 258) suggested the "ideal fabric" should contain four maxima arranged in a diamond pattern around the pole. Kamb (1959) argued that in stressed ice, the c-axes are all normal to the shear plane, but on stress release the orientation changes to a diamond pattern. Such a change has not been proven to occur. Further, Rigsby (1968, p. 250) concluded from a study of crystal shapes from glaciers that many axes plotted in one maximum really represent a single crystal, thus throwing some doubt on many published fabric diagrams. Hooke (1969a) suggested that such diagrams may be accepted at face value.

Thus c-axis fabrics are known to take on several characteristic patterns, but the mechanics of formation are

not well understood.

Most field studies on glaciers record only optic axis orientation, but Anderton (1969) considered other petrographic data.

Considering undulatory extinction, on theoretical grounds it is due to the permanent bending of a crystal, with a resultant change in optical properties (Fig. 3b). Steinemann (1958) showed that it occurs for inhomogeneous deformation, and not for homogeneous. Rigsby (1960) reports that strain shadows are rarely seen in temperate glaciers, but frequently in polar glacier ice and laboratory deformed specimens.

The Effect of Inclusions

The above review of laboratory experiments is restricted to work on pure ice. In the natural state, ice may contain impurities in the liquid, solid and gaseous phase, but work on ice containing such materials is limited. Rigsby (1960, p. 602) suggested that bubbles inhibit crystal growth by absorbing strain and preventing grain boundary migration. Weertman (1968, p. 155) discussed bubble coalescence as a tool for measuring active deformation. However, no detailed study of the effect of gaseous inclusions on laboratory controlled deformation has been made. Of more importance to this study are the relative deformabilities of pure ice and ice loaded with varying proportions of sand.

In the following review, physico-chemical properties of frozen soils are considered, followed by mention of changes in soil strength on freezing dependent on saturation and temperature. Loading of frozen soils is discussed in terms of changes in ice-sediment relationships. Subsequent to the review of laboratory studies, field evidence of relative properties of ice and ice with debris is examined.

Deformation of the Sediment-Ice System

The literature concerning sediment-ice deformation is less voluminous than that for pure ice. However, work on the properties of frozen ground has been reported, early studies being carried out in Russia by Tsytovich and Sumgin (1937). Before discussion is made of the mechanical properties of frozen soils, the structure of the material in the undeformed state will be described. We are considering a 4-phase system; solid mineral particles, ice matrix, water, and air.

(a) Physico-chemical properties

The structure and mechanical properties of the mass are significantly influenced by the physico-chemical properties of the soil. The resistance to shear developed by granular materials is largely due to friction between solid particles; in addition, clay particles possess cohesion.

Fine grained soils containing particles with high specific surface area may retain an appreciable percentage

of water unfrozen at temperatures below the freezing point of ordinary water (Williams 1964, p. 239). This unfrozen water which surrounds the clay particles is a function of the specific surface area, colloidal activity of clay minerals, and temperature (Dillon and Andersland, 1966).

On freezing, bulk soil volume may increase, with inmigration of water to the freezing front. The distribution of ice in the soil is a function of the direction of freezing, soil permeability, and time. Even with an external source of water, the increase of volume of a saturated sand on freezing is only a small percentage of total bulk volume (Tsytovich, 1963). Ice lens development in fine grained material causes a considerable volume increase.

(b) Soil strength

The strength of all saturated soils increases on freezing, due to adhesion between ice and soil particles. Frozen saturated sand may have a strength several times that of clay at the same temperature because a considerable amount of the water in clays remains unfrozen.

In partly saturated soils, frozen strength increases with higher water content up to a limit close to the full saturation point. For higher water contents, strength falls off and approaches that of pure ice (Tsytovich, 1963).

A temperature rise produces a variation in strength associated with ice quality and ice-particle adhesion changes.

(c) Loading

An external load produces stress concentrations at mineral-ice contact points, resulting in plastic flow and pressure melting of the ice (Barnes and Tabor, 1966). Tsytovich (1937) reported that meltwater migrates down the pressure gradient. Recrystallization at a point of lower stress occurs with the basal plane parallel to the slide direction thus reducing the shearing resistance. Simultaneously a denser packing of mineral particles occurs since vacant locations resulting from moisture displacement are filled with solid particles. This gives rise to molecular cohesion between particles (Vyalov 1963). Thus there occur two opposed phenomena in frozen soils under pressure: (a) weakening due to gradual re-orientation of ice crystals, and (b) strengthening due to increased molecular cohesion caused by closer packing of mineral particles.

Under loading sufficient to produce deformation, but below a certain threshold value, softening will be compensated by hardening, and a steady-state deformation rate will result. However, if the threshold value is exceeded, softening overcomes hardening, and undamped flow takes place. This threshold value defines the long-term strength of the soil (Vyalov 1963).

That ice structure changes as deformation proceeds has been established above. The initial volume increase for such samples is considered to be associated with disruption

of intergranular continuity by grain boundary sliding. Addition of sand to the system may act as a key to impede grain boundary sliding.

Goughnour and Andersland (1968) prepared sand-ice systems in which "sand particles are dispersed uniformly through the frozen mass". They found that at low volume concentrations of sand the increase in shear strength was a simple linear relation to relative proportions of sand and ice. It appears that the majority of plastic deformation is accommodated by the ice, thus the effective deformation rate for the ice may be considerably greater than the observed gross sample deformation rate. The keying effect of sand grains may occur, dependent only on the volume concentration of sand particles, being mobilized at all strains.

Hooke et al (1972) indicate that sand grains in deforming ice may be surrounded by clouds of dislocations which impede the passage of primary glide dislocations. Such a cloud was observed by Kuroiwa and Hamilton (1963).

Above a critical sand volume of 42%, Goughnour and Andersland (1968) noted a rapid increase in shear strength, which they presumed to be caused by friction between sand particles, and dilatancy, the latter acting against cohesion of the ice matrix and adhesion between sand grains and ice. Assuming saturated soil conditions, the degree of dispersion in frozen sand-ice samples depends on: (a) original void ratio; (b) permeability of the solid soil systems; (c) effective

stress on the solid soil skeleton during freezing, which may change as pore water is lost to ice lenses, and varies with crystal orientation; (d) rapidity of freezing. Initial loading led to a small volume decrease equal to the volume of small air bubbles.

A volume increase on continued deformation was considered by Goughnour and Andersland (1968) to be related to dilatancy of sand particles. The ice matrix effectively exerts a confining pressure on the sand particles which increases as the volume increase takes place. This confining pressure grows until either no more increment in volume is experienced, or the limiting cohesion of the ice is overcome. Stress-strain curves are shown in Fig. 4.

Field Studies

Evidence from field studies also suggests that ice containing a small percentage of debris deforms more readily than clean ice. Abel (in Swinzow 1962, p. 223) recorded increased differential movement across certain bands of included material. Swinzow (1962, p. 226) compares the deformation of debris bands with varying sediment content with that of surrounding clear ice. Bands with a small percentage of fine debris act as zones of weakness while higher concentrations of coarse material lead to less overall deformation. Swinzow (1962, p. 225) suggested a change in the flow law dependent on the included debris percentage.

For a given stress, the strain rate is to be multiplied by a factor "i" which increases as the sediment increases, provided included particles are not touching.

Thus $\dot{\varepsilon}_{\text{silty ice}} = \dot{\varepsilon}_{\text{ice}} \cdot i$ for a specified stress. Swinzow argued that particle contacts serve to reinforce the mass, the strain rate becoming less than that for pure ice.

A further point is the possibility of increased deformation due to changes in the liquid layer at grain boundaries. Nakaya and Matsumoto (1953) demonstrated the presence of a liquid-like layer on ice. This was confirmed by Hosler et al (1957) and Jellinek (1965). Morainal material might affect the thickness of the layer, the more soluble components being concentrated at grain boundaries. An increase in intergranular movements is to be expected under the above conditions.

Conclusion

From the above review, it is evident that pure ice and ice with sediment have different deformational properties. Evidence from laboratory and field studies support this conclusion. Thus in the study of the folded ice in Tuktoyaktuk, separate consideration must be given to ices with different sediment contents, the gradations between sediment-rich and sediment-free ice being of particular interest.

Considering the pre-deformational state of the bedding as parallel banding of ice and icy sediment, suggestions may be made concerning the response of the body to an imposed stress. In the relatively pure ice, some crystals accommodate the stress by basal slip, if suitably oriented. Others may rotate, suffer strain build up, become polygonized, or crack. If rotation of many crystals is possible, lattice preferred orientations occur, productive of maxima on fabric diagrams. Build-up of strain is characterized by strain-shadows and deformation bands, where individual segments of crystals show slightly different optical orientations. Cracking has been recognized in laboratory experiments but has not been reported from glacier studies. In dead ice, cracks would be obliterated by recrystallization. The process of recrystallization is active throughout deformation (syntectonic recrystallization) and later (post-tectonic recrystallization). Where contiguous strained grains recrystallize without the formation of new nuclei, mutual outgrowths of unstrained material gives sutured grain boundaries. If nuclei grow to give new grains these are characteristically strain-free and may embay old strained grains. In the presence of directed stress during post-tectonic recrystallization new grains will tend to be equant, in contrast to the old grains which show dimensionally preferred orientations due to flow.

The presence of inclusions, notably sediment, in an ice specimen leads to increased deformation of the ice, volume

for volume. Thus in a sequence sediment-free ice/icy sediment, different deformation rates would be expected for a constant imposed stress. In the field complications arise due to fluctuations in temperature, stress value and stress direction.

It is expected that application of the above principles to the body of ice under investigation may allow recognition of differing generations of crystals and elucidation of the overall mode of deformation.

CHAPTER IV

METHODOLOGY

Introduction

The major objectives of this study are to analyze the mechanism of deformation of the folded sand-ice sequence and to infer the pre-deformational growth of that sequence. Other purposes are to infer the post-deformational history of the body and to ascertain distinctive features of the ice and contained sediment for future field recognition of the ice type from limited core samples.

Chapter Outline

It was necessary to map the mesoscopic structure to elucidate the fold geometry at that scale. Thin sections of known orientation were prepared from the available exposure, necessitating a multi-stage sampling plan: (a) sampling of folded material; (b) sampling of blocks from (a) for thin section preparation; and (c) sampling thin sections.

The errors of the Universal Stage technique are examined and in addition those peculiar to ice studies are enumerated. Discussion is made of the plotting of optic axis orientations, the number of points necessary and contouring methods for scatter diagrams. The interpretation of diagrams and tests

of significance of minor concentrations suitable for field use are considered. Axial Distribution Analysis (A.V.A.) is described.

Scale Considerations

The determination of the fabric of a body begins at the scale of the exposure, called mesoscopic scale (Turner and Weiss 1963). The principal fabric elements on this scale are foliation attitudes, folds and lineations. A series of mesoscopic studies is then synthesized into the overall fabric of the body--the macroscopic scale. In the Tuktoyaktuk ice cellar the macroscale cannot be considered as analysis is confined to one major exposure; extrapolation to a larger body is not justified. However, the lateral extension of the body has been mentioned by Rampton and Mackay (1971) on the basis of air photographs after a storm. The body is also studied on the microscopic scale--principal elements are shape and crystallographic orientations.

The Symmetry Principle

The concept of symmetry in the interpretation of deformed rocks was established and developed by Sander (1930). Paterson and Weiss (1961) reviewed the concept of symmetry in physics and related sciences and have placed the application of the concept to tectonites on a rigorous basis (p. 841):

> "Whatever the nature of the factors contributing to a deformation may be, the symmetry that is common to them cannot be higher than the symmetry of the deformed fabric, and symmetry elements absent in this fabric must be absent in at least one of the contributing factors".

The symmetry of a homogeneous stress cannot be lower than orthorhombic and the symmetry of distortion in a homogeneous strain must have orthorhombic or higher symmetry.

Mapping of available exposure

In order to determine the deformational history of the body, it is necessary to ascertain as completely as possible the present configuration of all exposed features. At the mesoscale this requires measurement of attitudes of foliation, lineations and fold axes in the field. The exposure with its foliations was mapped at the scale 1 cm represents 10 cm. A foliation is a recognizable discontinuity or layered structure in the ice mass. The major foliation in this study is the compositional layering exhibited by differing sediment content. The fold form and other structures and their interrelationships were analyzed and folds classified by style. On this basis, a sampling plan for microscopic study was prepared. With the usual geological nomenclature, surfaces are designated S_0, S_1, S_2, etc. in the following discussion. Here S_0 is taken to be the pre-deformational bedding; S_1 is the axial surface (Fig. 6).

Fold characteristics

Folds are characterized by:-

1. Similarity in shape from one layer to another
2. Persistence of the fold through appreciable stratigraphic thickness
3. Relative lengths of limbs
4. Attitude of axial surfaces relative to the prevailing attitude of stratification
5. Closeness of appression of limbs
6. Relative bed thickness around the fold closure.

From a preliminary reconnaissance of the fold morphology throughout the cellar, folds were categorized into three styles (Fig. 7).

Style 1 Folds

These folds have closely appressed limbs, dihedral angles being less than 30°, thus the folds are tight to isoclinal (Fig. 7a, 8) (terminology after Fleuty 1964, p. 470). Axial surfaces are parallel to the general attitude of the compositional foliation. Bed thickness varies, thickening occurring at fold closures. In some cases attenuation of limbs is extreme, leading to "rootless" folds where fold closures remain (Fig. 8).

Style 2 Folds

These folds are asymmetrical, one limb being long, the other short. Axial surfaces are inclined to the prevailing compositional layering. The folds are not

persistent through much stratigraphic thickness. Minor variations in bed thickness occur around the fold (Fig. 7b). Folds occur in beds which were traceable over distances many times the fold limb length.

Style 3 Folds

Only one example of this fold type was found (Fig. 9). The fold is characterized by its more open nature than the Style 1 folds into which it passes vertically and laterally. Its axial surface is at approximately 45° to the general compositional layering. Exposure of limbs to depth is lacking, but there is a recognisable thickening in the fold closure. There is a marked asymmetry in terms of limb length.

Sampling Methods

Having mapped the exposures, the next objective was a detailed petrographic study of the ice body, including the production of fabric diagrams of optic axes of crystals, and analysis of grain size and shape characteristics. For these investigations, representative thin sections were to be produced, necessitating a several-stage sampling method.

(a) Sampling folded material

The limitation of exposure to cellar walls led to the cellar being considered as a population in itself and requiring as complete sampling as possible. Having defined this population,

the next step was to devise a sampling plan for folded material. Fold hinges in such highly deformed material (isoclinal with extended limbs) have much smaller volumes and areas exposed than the corresponding limbs, so the use of a regular system of sample points would give few measurements of hinges. These latter are of especial importance as the relationships of S-surfaces are most readily investigated there; also bed thicknesses have greatest variations, compared with more uniform thickness on limbs. Whitten (1966) refers to the desirability of stratifying the sample on the basis of lithologic type or the thickness of members. Further it is argued that a plan could be based on material types defined by different metamorphic grades or zonations. However, as pointed out above, the available sample is limited in the vertical dimension, where greatest variation would be expected. On the basis of the map of fold geometry, folds were grouped by style, as described above. From each sampled fold, several blocks of known orientation were cut as indicated in Fig. 10.

The blocks were sawn from the face, geographical orientation being denoted by characteristic marks on each surface. Also the strike and dip of each face was measured by compass-clinometer, and recorded, with a sketch or photograph of each sample.

(b) Sampling of Blocks

From each sample block, several thin sections were cut at various orientations. Sequential sections parallel to the compositional foliation were taken on fold limbs and at fold closures. Vertical sections in 2 planes were prepared throughout the body (Fig. 11). From the first block a randomly oriented section was cut, and optic axes plotted to give an indication of any preferred orientations. Conclusions drawn from this diagram facilitated planning subsequent section orientations to reduce errors due to equipment (Langway 1958, p. 8; Bader 1951). It was found practical to cut horizontal sections, and vertical sections both parallel and perpendicular to the fold axis. Thus, as shown in Fig. 11, from each sampling station, sections of three different orientations were employed; also random sections were produced and rotated into the horizontal or vertical plane to test homogeneity at a given point. In many cases, a given section contained over 100 grains. However, where several sections were cut close to each other at a given station, the chance of repeated measurement of one ice grain was either avoided by cutting horizontal sections in the same plane, or minimized by cutting horizontal sections at a vertical separation of 5 cm. Further checks were to observe grain boundary outlines during melting, and to cut vertical sections mutually perpendicular and observe crystal patterns. No complicated interlocking shapes such as described by Rigsby (1968) were found.

Thin Section Preparation

A given section of known orientation was smoothed on one side and then frozen onto a thin plate and melted on its upper surface until individual crystals were easily visible. As the work was carried out below -10°C, in an ice house and also in a deepfreezer, section thickness was easily controlled. Prepared sections were mounted on a Rigsby universal stage, and further thinned if necessary to maximize accuracy of extinction angle measurement. Some workers mounted specimens between plastic discs to prevent movement. This adds an error due to the refractive index of plastic sheets; also such sections disintegrated, which may have lead to incorrect readings.

Universal stage technique

Description of the standard technique of orientating crystals on the Universal Stage may be found elsewhere (Emmons 1942; Langway 1958).

Errors

Langway (1958, p. 8) enumerates four sources of error in measuring c-axes. Further errors reported by other workers, and those found in this study are listed.

(1) Measurement of exact extinction position at high angles

(2) Parallax effect when the eye is not normal to the measured grain

(3) Operator error in reading orientation dials

(4) Inherent mechanical errors in the stage itself (reproducibility of readings from the same grain is usually between 1° and 2°).

(5) Measurement of crystals in the equatorial position where extinction is less distinct than in the polar position.

(6) Perfect orientation of the thin section may not be maintained due to inaccuracies of cutting blocks from the ice face, and sectioning of the blocks. A test of such accuracy is the comparability of diagrams.

(7) The probability of multiple measurements of a single crystal has been reduced, as discussed previously.

(8) Work on temperate glaciers necessitates the use of thick sections of the order of 1/16", as uncontrolled melting continues during the measurement of only 10 to 20 grains per section, before disintegration. Thus many sections were necessary to produce a given diagram, further increasing errors. In the present study, sections could be reduced to approximately 0.5 mm (estimated from interference colours) thus allowing more accurate measurement of extinction. Also, all grains in a given section could be measured as disintegration was impossible at the prevailing temperature.

(9) Due to the high sediment content in some sections, irregular melting occurred; thus some small crystals among sediment grains were not measurable.

Allowing for equipment errors, fabric diagrams are considered representative.

All sections were photographed both with and without polaroids; all were stored for future reference, for example checking some points after plotting.

Plotting of Optic Axis Orientation

All orientations, polar and equatorial, are corrected for refraction at the ice-air interface (Langway 1958, p. 7). No hemispheres were used on the stage.

Corrected readings were plotted on the Schmidt equatorial equal area net. A unit area anywhere on this net corresponds to a unit area on the sphere from which the net was derived, but with distortion of shape.

Petrofabric diagrams illustrate the 3-dimensional orientations of fabric elements in a complete and concise manner. Conventionally, orientations are shown relative to a reference plane (the plane of the diagram) in lower hemisphere equal area projection. In many cases the point pattern is obvious, a point concentration or girdle, and contouring is unnecessary. Although such strong groupings were found in this study, contouring was carried out for comparison with many published diagrams from glaciers showing multiple maxima, and those

from ground ice. The literature of glaciology and of metamorphic petrofabrics in general abounds with discussion concerning the number of points necessary, how they should be contoured, what constitutes a preferred orientation, and the validity of Axial Distribution Analysis.

(i) Number of Points

The number of grains measured has ranged from about 25 (Bader et al 1939) to 300 (Kizaki 1969a) most workers plotting over 100.

(ii) Contouring

A scatter diagram may be contoured to emphasize the orientation pattern. Generally contours are based on the number of points per unit area of the net, usually in percentages. A counting area corresponding to 1% of the area of the Schmidt net is centered on the intersections of a predetermined grid, and the number of points in that area are recorded. A contour surrounds a given density of points. An error enters in the arrangement of the counting grid, and in the subjective nature of contouring and interpretation of contour shapes. Only the centre of gravity of a maximum, or the trend of a girdle can be considered meaningful; local vagaries of contours in many published diagrams are not of significance.

In this study, a sequential sampling technique was used,

plotting continuing during grain measurements, until no significant difference ensued from plotting the latest axes. In general approximately 100 grains produced single maxima of 15% or over. In such cases, 100 grains, 125, 150, etc. were measured for ease of percentage contouring. Sections of several orientations were analyzed at each sampling point, and by rotation to a common plane, a composite diagram of several hundred grains was prepared. Also, synoptic diagrams from sections around a given minor fold were drawn.

(iii) Interpretation

The first problem in the interpretation of contoured diagrams is to decide whether the diagram shows a preferred orientation, i.e., that it differs from that expected for an isotropic orientation of grains in the parent material. Flinn (1958, 1963) examined several of the widely-used tests of significance and found them unsuitable. The statistical (rather than glaciological) significance of clusters and girdles of points may be tested against null hypotheses. The usual null hypothesis is that of complete randomness. Flinn (1958, p. 533) prepared a random diagram. Comparison with the diagrams constructed in this study indicates that they all exhibit preferred orientation.

The probability that point diagrams contain concentrations deviating from a random distribution is approximated by the Poisson distribution. The probability P of obtaining

at least x points in any 1% area of a fabric diagram is expressed by:

$$P = \sum_{x=x_1}^{x=\infty} \frac{e^{-Np}(Np)^x}{x!}$$

N = number of points sampled

p = probability that 1 point occurs in a given 1% area (here 0.01)

When Np = 1,

Probability	% concentration c-axes/1% area
0.63	1
0.26	2
0.08	3
0.02	4
0.004	5
0.0006	6
0.0001	7

Thus for a 100 point sample (Np = 1) the chance of a 7% concentration is 1 in 10,000.

The above concerns statistical, not glaciological significance. For example, minor concentrations within a general pattern such as a girdle may have no significance. In the present study, the listed probabilities were used for comparison with concentrations obtained, rather than to attach a significance level to a local concentration within a given orientation pattern.

Axial Distribution Analysis (A.N.A.)

Having established that the diagrams provide evidence that preferred orientations exist in the body, it is necessary to determine whether or not grains of different orientation are homogeneously or inhomogeneously distributed within the body. The method is called Axial Distribution Analysis (A.V.A.). In this study, the method was applied to small folds contained within a thin section. A drawing was made, and the folds divided into fields corresponding to (a) fold hinges, and (b) fold limbs. Optic axes from crystals within given fields were plotted on separate diagrams and compared for homogeneity. It was found that diagrams from component fields were identical to those of the composite field, within the degree of reproducibility of the diagrams.

Measurement of Ice Crystal Size and Shape

Although grain sizes in the ice are on average much larger than grains in many rock and metal thin sections, accurate measurement directly on the Universal Stage is impossible. Thus photographic slides were prepared for sections and projected onto gridded paper. Measurements were made of area and major and minor axes, to give 2-dimensional size in 3 mutually perpendicular planes and thus an overall picture of dimensional preferred orientation in relation to foliation, and inferred deformational directions. Records of crystal size in the literature are often based on the

product of 2 major axes averaged over 100 grains; these measurements were taken here for comparison.

In addition to size calculations, grain shape characteristics were studied from the slides. Triple-points of grain boundaries were measured, to give an estimate of thermodynamic equilibrium.

Sediment Content Analysis

From figures of folds and thin sections (Figs. 8, 9, 10) it is evident that sediment content varies greatly. The amount of sediment in a thin section is insufficient for estimation of dirt content by areal measurement. Thus a series of blocks was cut in a vertical line from the core of a fold, and the volume of excess ice calculated. Total weight of a sediment-ice sample was measured, then the weight of ice and of dry soil calculated to give the ice content by percent of dry soil.

Sediment Size Analysis

Analyses were made of the sediment obtained from samples taken for sediment content analysis, and from samples removed from beds, boudins and lenses. The latter included beds containing sedimentary structures. Standard sieving and hydrometer methods were employed.

Conclusion

The methodology employed has been designed to sample all fabric elements in the available exposure. From fold morphology, inferences may be drawn concerning the mode of deformation to produce the geometrical configuration at the mesoscopic scale. On the microscopic scale, features may be related to the mesoscopic foliations. These features are ice grain optic axis orientation, dimensional orientation, grain size and shape. From the discussion of deformational and recovery properties given in Chapter III, the petrofabric features indicate modes and directions of deformation. Also age relations of mesoscopic and microscopic forms may be inferred from indicators of intensity of deformation, such as fold style, symmetry of fabric diagrams, and from periods of crystal growth.

CHAPTER V

RESULTS

Introduction

Consideration has been given to the known deformational characteristics of ice with varying sediment contents. Results of applying the methodology of Chapter IV are discussed in this chapter, the aim being to elucidate the mechanism of deformation of the ice in Tuktoyaktuk.

Chapter Outline

This chapter deals firstly with mesoscopic structure, and then the microscopic aspects of the deformed ice. The overall mesoscopic structure is subdivided into three fold styles introduced in Chapter IV. Each style is considered separately in detail, then interrelationships among fold styles are discussed and an overall interpretation of deformational movements from mesoscopic structure is given. Then, the results of microscopic studies are discussed. Optic axis distributions from thin sections from around individual folds are related to mesoscopic foliations, and details of the mode and direction of deformation inferred for individual folds and the overall fold form. Grain shape characteristics

from the several fold styles and the two foliations are compared, and local variations of deformation and recrystallization inferred.

Ice grain size is determined from three mutually perpendicular thin sections, variations in size being related to local changes in foliation. Because of the irregularity of grain shape, only average measurements of grain size are possible.

Sediment grain size, shape and concentrations are discussed. Water quality analyses are tabulated and inferences made.

An overall interpretation of the pre-deformational state of the bedding and its subsequent folding is given.

A. STRUCTURE

1. Overall Mesoscopic Structure

Folds of Style 1

These folds dominate the structural geometry, occurring throughout the available exposure. Individual folds are traceable for long distances, the axial surfaces being subhorizontal and thus parallel to the floor of the cellar. Fold amplitudes reach several metres and wavelengths up to 1 m occur. Bed thickness varies considerably in a given bed, and from bed to bed. In the more regular folds the thickness ratio of limbs to hinges measured radially is 2/9 on thirty beds.

The complete thinning out of beds on limbs occurs in many places (Fig. 8). The possible reasons are two-fold:

(a) pre-deformational state of the bedding, and (b) a feature of deformation. As the thinning occurs in beds which are thick at fold closures it is reasonable to suppose that the feature is a deformational product, otherwise "limbs" would occur with no closures. Such are not common. However, transposition structures and boudinage occur (Figs. 12, 13). Boudinage is common in strongly deformed rocks, in which an originally continuous competent layer between less competent layers has been stretched, thinned and subdivided into bodies elongated parallel to the bedding (Fig. 12a, b). In this study the boudins have rounded outlines, indicating that under the conditions of deformation, the competencies of the beds involved were not very dissimilar, but the boudinaged layer having less capacity for stretching. The boudins are not completely separated from the initial bedding (Plate 2).

Folds of Style 2

These folds are confined between plane or unfolded sections of fold limbs, and are asymmetrical (Fig. 7). They are thus drag folds, formed by the relative movement of the enclosing layers. The short limb was rotated from its original position, the sense of rotation indicating the sense of movement in the enclosing layers. Axial surfaces are oblique to the compositional foliation and thus to the axial surfaces of Style 1 Folds. Fold axes are parallel to those of Style 1 Folds.

Folds of Style 3

Only one example of this Fold Style occurs associated with a lensose sand body which reaches over 40 cm thickness in a direction at right angles to local bedding. The lateral and vertical gradation of this fold into folds of Style 1 indicates that the sandy body absorbed much of the deformational strain, allowing the Style 3 Fold to retain its observed morphology (Fig. 9).

Interrelationship among Fold Styles

Within the limited exposure the various Fold Styles can be related. Style 2 Folds occur as drag folds on extended limbs of Style 1 Folds. It is argued that they developed early in the deformation and became flattened with the Style 1 Folds.

The Style 3 Fold is unique. Its continued existence in its present orientation, with the axial surface at the high angle of 45° to the overall subhorizontal structural pattern, indicates that it has survived the flattening and stretching episode recorded in the Style 1 Folds. It is thus a relict of an early stage of deformation. The position of the fold close to the large sand lens (Fig. 9) suggests that later strains were largely absorbed by that sandy body.

Interpretation of Movements from Mesoscopic Structures

From the overall mesoscopic structural pattern, it is evident that the Style 3 Fold is representative of an early

stage of the deformation. Its more open mesoscopic form and the orientation of its axial surface relative to the local structures are evidence of this. Further, the marked change in fold style in a lateral distance of 2.0 m and a lesser vertical distance, from Style 3 to Style 1 folds indicates the protective influence of the sand lens in absorbing strain.

In contrast to the Style 3 Folds, Style 1 Folds have tightly appressed limbs, indicating high ductility at the time of folding. The recumbent attitude with axial surfaces parallel to the prevailing foliation suggests strong flattening from the early Style 1 form into the presently observed style.

Style 2 Folds formed during the development of Style 1 Folds by drag of relatively moving limbs. Some flattening has also occurred.

A post-folding shear is shown in Fig. 14. Within the lower limb of the major fold, intergrain friction reduced deformation, whereas at the interface between predominantly sandy and predominantly icy beds, motion was favoured, giving rise to S-shaped structures within the sandy bed. After fold formation, a shear developed above the syncline, as indicated by the juxtaposition of two synclines.

2. Microscopic Structure

Further study of fold structure was made on thin sections.

Style 1 Folds

One such fold was subjected to detailed sectioning for the purpose of determining optic axis distributions. These sections were also analysed for fold style. Bedding foliation was found to be continuous around the fold closure in this case, no major offsetting being displayed (Fig. 10). A second fold of Style 1 showing asymmetrical form was studied. In this case, offsetting of thickened bedding in the fold closure is evident (Plate 3). Offsetting occurs parallel to the axial surface. This is in agreement with the suggestion, based on mesoscopic structure, that stretching of folds occurred, movement occurring parallel to axial surfaces.

Style 2 Folds

These folds are mainly of microscopic scale, individual folds being contained within a given section. From Plate 4 it is evident that axial surfaces are oblique to local bedding, several crests occurring close together.

Style 3 Folds

Several sections cut at right angles to the fold axis were analysed. On the microscopic scale, the boundary between sandy and icy layers is abrupt. Individual sediment bands may subdivide as shown in Fig. 10, and show thickness variations not related to the present state of folding.

3. Microscopic Fabric

Deformational movements in the body have been inferred from the analysis of mesoscopic and microscopic structures, assuming idealized mechanisms of folding and flattening. In order to gain a better understanding of the actual deformation mechanism, microscopic fabrics of selected specimens were studied. These specimens were collected on the basis of the sampling plan discussed in Chapter IV.

General Petrography

A simple subdivision was made on the basis of the composition of layers. Ice bands are fairly pure, with dispersed sediment. Crystal size varies from 0.06 cm^2 to over 20 cm^2. Dimensional preferred orientation parallel to the fold axial surface occurs. Strong undulatory extinction is common, also smaller unstrained grains with regular outlines. Several textures, including highly sutured grain boundaries and mimetic recrystallization are found (Figs. 15, 16).

Sediment bands have high sediment content (Table 2) and ice crystal size is limited by spacing of sediment grains. The difficulty of producing thin sections in the material meant shapes and extinction characteristics were less well studied than in predominantly ice bands.

Contacts between ice and sediment bands are irregular and occasionally gradational. A more detailed discussion of textures is given later.

Origin of Fabrics

The origin of a preferred orientation of crystals during deformation is attributed to reorientation into supposed slip directions in the deforming body as a whole. A given thin section does not contain a fold, but sampling techniques made it possible to relate fabrics from sections to features of the major structures.

The Petrofabric Approach

The work of Sander (1930, 1948, 1950) and Schmidt (1932) established the concept of mineral orientation symmetry, i.e., optical or dimensional orientation is related to major structures in deformed geological bodies.

The term fabric (Gefuge) comprises all spatial data; it was found practical (Sander and Schmidegg 1926) to refer these data to 3 mutually perpendicular axes, a, b, c. Sander (1930, p. 56) defined the axes with respect to relative movements; thus a represents the direction of greatest displacement in the slip plane; b is perpendicular to a and contained in the slip plane; c is perpendicular to the ab plane.

(a) First Style 1 Fold

The first major fold to be sampled is shown in Fig. 10. Five ice blocks were removed from around the hinge zone as indicated; further blocks were cut on the limbs where S_0 and S_1 are sub-parallel, to study any changes in fabric throughout.

Considering block 1, this was cut so as to contain both relatively clear ice above, and several sediment bands below. To maintain orientations, measurements were taken of strike and dip of all faces, also a N-line and several horizontal marks were made as a further check. From this block, multiple sections were prepared, in both horizontal and vertical orientations, in which a total of approximately 400 c-axes were measured.

The fabric diagrams are drawn in their original plane. As projections are mutually at right angles, it is easy to picture mentally the rotation of one diagram into the plane of another. Diagram 1 represents 100 grains from the upper relatively clean ice of the block, in a horizontal projection. A single broad concentration is indicated, with a maximum of 19% axes per 1% area, centered approximately 13° from the pole of the plane of projection, which coincides with the c-axis of the fold in the field. Minor concentrations of no greater than 2% at 60° to 80° to the c-axis can be given no significance.

Continuing the study of the upper ice, a further section was cut parallel to the bc plane. In this case (Diagram 2) the concentration parallel to c persists, with a maximum of 16%, but secondary maxima appear, lying approximately in the bc plane. These represent crystals measured in the equatorial extinction position, which is considered to be subject to some error; however the strength of the

concentration, and the coincidence with minor maxima in other diagrams suggests geological significance. This is discussed later.

In order to investigate any fabric changes associated with the sediment bands, a vertical section was cut below the previous, in the same plane. This section included sediment bands.

Fabric diagram 3 again shows the characteristic maximum of 15% per unit area, from a total of 100 large crystals, between the sediment layers. Crystals within the sediment bands were of diameter smaller than could be measured due to the difficulty of thinning the ice between sediment grains. Minor concentrations occur approximately in the same plane as before.

Block 2 was cut from the hinge zone of the fold, and sections prepared in the horizontal plane, i.e. parallel to the axial plane, at several levels, also vertical sections parallel to the fold axis, at right angles to that axis, and oblique to that axis.

Diagram 4 representing a horizontal thin section shows 3 maxima arranged in part of a small circle centred approximately 10° from the vertical axis in the field.

A further horizontal section from below the previous shows a broader concentration surrounding the vertical axis with maxima of 20% and 9% (Diagram 5).

Vertical sections were produced in order to investigate the variation in the 2 horizontal sections. Diagram 6 represents 175 crystals measured in a vertical section parallel to the fold axis. The dominant characteristics are 2 maxima of 10% and 12% closely associated with the pole to the axial plane. A weak girdle of 1% to 2% traverses the diagram, indicating axes in a vertical plane perpendicular to the local fold axis. These are considered to represent the influence of local bedding around the hinge.

A vertical section oblique to the fold axis was prepared, this again showed a maximum of 12% (from 100 crystals) in a concentration around the pole to the axial surface. A girdle with local grouping of up to 7% was found, after rotation of the section into parallelism to the foregoing (Diagram 7).

Diagram 8 represents 100 crystals in a vertical section perpendicular to the fold axis. Two maxima occur within one major concentration signifying c-axes at right angles to the local axial plane. No girdle is seen comparable to those in diagrams 6 and 7, as the fold hinge in sediment is not included.

Block 3 was removed from the ice-face at the position shown in Fig. 10.

Three horizontal sections were cut at vertical separations of 7.5 cm, from which measurements of 300 grains were taken. Small crystals associated with a minor sediment

band were plotted separately from the remaining large crystals. The diagrams (9, 10) show a strong concentration around the pole to the axial surface; the small grains have axes distributed in a cone of 15-20° radius around the pole (Diagram 9). Such an arrangement has also been found in recrystallizing quartz by Voll (1960, p. 520).

A vertical section parallel to the fold axis gave 100 axial orientations plotted in diagram 11. A small circle of 20° passes through the maxima.

During the course of analysis of the ice blocks discussed above, it became apparent that sediment bands exerted some control over crystal axis orientation. Thus block 4, from the lower limb of the fold was subjected to successive horizontal sectioning at 5 cm vertical intervals, from a pure ice layer down to a sand band. The composite diagram and component diagrams are presented in Diagrams 12-16. The several concentrations in the composite diagram are broken down among the serial sections, for example one of the maxima at 40° to the pole of the foliation is absent from the final diagram. The maximum is the major feature of the upper section. Although the sample size in some component diagrams is limited, the change in distribution of concentrations is systematic. Further, it is pointed out that such changes might not appear on composite diagrams from glacier studies where component fabrics are not plotted singly.

The final block in the fold hinge area, block 5, contained a narrow sediment band near the top. Horizontal sections were prepared from three positions, one above and two below the sediment. A 13% maximum shows in the fabric diagram (17) at the pole to the axial plane. But there is a complicating factor in the presence of a sub-horizontal sediment band on which relative movement would occur.

Secondary maxima of up to 7% and 9% occur on a partial girdle containing the first maximum. Large crystals in the upper section are distributed evenly among the three concentrations. Both large and small crystals in the lower sections have axes oriented approximately vertically.

(b) Style 2 Fold on First Style 1 Fold

A further section was taken, shown in plate 4, and oriented vertically, perpendicular to the fold axis. As the diagram (18) of the section shows, minor folds occur on the sub-horizontal sediment bands, with thickening on crests, relative to "limbs". These are Style 2 Folds. The fabric diagram has a broad concentration containing several maxima, of up to 12% at right angles to the foliation.

(c) Interpretation of Fabric of First Style 1 Fold

Considering firstly the fabrics where no sediment occurs, the ice subfabrics are homogeneous throughout the fold. That is, the patterns are identical, within the degree of reproducibility expected, regardless of position on the

fold. The symmetry type is axial, and at the lowest degree, orthorhombic. The symmetry axis coincides with the pole to the axial surface, this surface being a symmetry plane. But the bedding foliation is inclined to this plane throughout the hinge area. The influence of sediment bands is seen in other fabric diagrams, namely the presence of minor girdles corresponding to bedding (Diagrams 6, 7). Thus earlier preferred orientations are maintained by some grains, whereas the earlier orientations were obliterated where the constraint of sediment was not operative.

The symmetry suggests that maximum compressive stress and the axis of greatest shortening was perpendicular to the axial surfaces, resulting in appression of the fold limbs to their present isoclinal character. Thickening of layers in hinge regions is consistent with this interpretation.

(d) Second Style 1 Fold

As Fig. 17 shows, the progressive development of a fold can be followed; this area was studied in the previous manner. There again occurred a concentration of sub-vertical c-axes as shown in diagrams 20-23, where > 1 maxima occur.

Considering a horizontal section on the lower limb of the fold in Fig. 17, axes were plotted separately, sub-division being made on the basis of position relative to sediment bands. No significant change is apparent, other than the presence of a 6% concentration of axes in one section parallel to the fold axis, but in the horizontal plane. This

is concomitant with movement in the direction of major transport, but in a vertical plane. However no such structure was evident in the field or in the section. The particular grains are not parts of one large crystal, but are distinct entities, distributed along a sediment band. This is a local feature, not repeated on other diagrams.

A second series of horizontal sections produced the fabrics shown in Diagrams 24-27, separately plotted on the basis of position relative to local sediment bands. The composite diagram indicates a small circle distribution, radius approximately 20° around the vertical field orientation, including 3 maxima of 8, 13, 18% respectively. The pattern is repeated in two of the component diagrams, and suggests a recrystallization fabric, as pointed out above.

(e) Third Style 1 Fold

A further series of sections was prepared from a third Style 1 Fold. A total of 250 grain orientations from 4 sections gave rise to the fabric in diagram 28. This composite diagram is broken down into 2 components, each of 2 adjacent sections in 2 horizontal planes 5 cm apart. The same broad pattern exists in each. A further fabric comprises grains in a sediment layer contained in the lower section; the diagram shows less areal spread, and the absence of a previous maximum. Although the latter diagram (31) is based on only 35 crystals, the concentration is marked and tends towards a small circle pattern.

(f) The Style 3 Fold

The open folds and the lateral and vertical gradients into tight structures have been referred to previously (Fig. 9).

The fabrics representative of these open structures are markedly different from those of earlier sections. The several vertical sections perpendicular to the fold axis show cleft girdles in the plane of the diagram. The pattern of preferred orientation for all sections and parts of the fold is similar; thus the fabric is homogeneous throughout the fold (Diagrams 32, 33).

Mode of Deformation, As Indicated by Fold Morphology and Optic Axis Distributions

Thus the pattern of deformation throughout the body is considered to be similar to that of the small open fold, i.e., Style 3 Fold, with girdle-type fabric in the early stages, the limbs then becoming highly stretched, and brought into parallelism with an axial planar "schistosity". Rotation of grains during accommodation to the imposed stress has changed the fabric of optic axes to one of maximal orientation perpendicular to axial planes throughout the body. At hinge zones offsetting of bedding parallel to the axial surface is indicated (Plate 3), and the lattice fabric at hinge stations shows the characteristic form, but with relict features from an earlier stage in the deformation, namely a minor girdle as shown in diagrams 6 and 7.

Some relative movement occurred within some of the sediment bands, depending on particle content; thickening of fold hinges occurs in places. Boudinage with lensoid outlines and deformed sedimentary structures have been discussed, and are indicative of intense stretching.

Such are the conclusions drawn from an inspection of fold morphology and optic axial distribution of the sections described. The next section deals with grain shape, size, dimensional orientation, evidence of straining, and the influence of sediment bands, dispersed sediment and gaseous inclusions on those characteristics.

B. ICE GRAIN SHAPE

Introduction

Grain shape in polycrystalline aggregates is an important parameter in the study of the body's history. In the case of a monomineralic material such as an ice body devoid of sediment, the existence of the grain boundaries is indicative of differing lattice orientations of the grains on each side. Knowledge of absolute and relative sizes of contiguous crystals in a deformed mass, and the curvature of their mutual boundary and strain within the individual crystals allows inferences to be made concerning the occurrence of grain boundary migration, recrystallization and overall deformation of the body. The presence of other phases, such as sediment, in the ice exerts

controls on grain shape. In the deformed body under consideration, there exist volumes of ice effectively devoid of sediment while elsewhere sediment is heavily dispersed both intergranularly and intragranularly, or occurs in recognizable bands. Under a given temperature-stress system, differential mobilization and complicated flow patterns result.

(a) Single Phase Material

Considering firstly a single phase aggregate, the influence of sediment is ignored. Characteristics of grain shapes in monomineralic materials have been studied by metallurgists, geologists (notably on quartzites) and later by glaciologists. A classification has been established: straight, curved, sutured, cuspate, etc., as shown in Fig. 18. MacGregor (1951) pointed out that sutured boundaries occurring between slightly undulose and strained quartz (resulting from strain-induced boundary migration, according to Flinn (1965, p. 55)) also occurs in ice. In the case of straight boundaries, thermodynamic equilibrium is suggested, but where unequal angles occur at triple points stability has not been reached. This also applies to curved boundaries which typify textures locked while mutually adjusting.

As pointed out previously recrystallization is a time-dependent process. At any stage during the evolution of the final texture, grain boundary types differ. The following may occur:

(a) early boundaries, which are normally destroyed during metmorphism.

(b) arrested boundaries, where equilibrium has not been achieved. A temperature decrease causes reduced grain boundary mobility, leaving a curved, sutured or irregular shape.

(c) equilibrium boundaries indicate low free energy, and are straight or slightly curved.

Thus the texture displayed in a given section is a function of earlier textures, the laws of nucleation, growth and cessation of growth. Shapes are subject to the requirements of space filling without gaps. There are also rules involving the configuration which an aggregate of grains must adopt in order to be in equilibrium under the influence of interfacial energies of grains. If thermal energy is available, diffusion transfer occurs. Free energy must tend to a minimum, so grain shapes and boundary relationships must alter to make this possible.

The direction of boundary migration depends on the availability of strain. A strain-induced boundary migration moves from an unstrained into a strained region. Movement of the curved boundary is away from its centre of curvature, leaving behind it strain-free material of the same orientation as the parent grain, with an associated increase in surface area.

Conversely, during the late stages of annealing, adjustments take place in unstrained grains; boundaries migrate towards their centres of curvature, and straighten, reducing their surface area, and surface energy.

(b) Effect of Inclusions

The introduction of inclusions into the pure ice system affects the shape of crystals, the distribution of the secondary phase (in this case sediment and gas) determining the relative mobilities of the boundaries. Considering the ice-sediment system, sediment bands effectively pin down ice-ice boundaries. Where a given crystal encounters one such sediment band, the crystal is elongated parallel to that band, and the grain boundary meets that band at right angles (Fig. 15); the result is exaggerated where contacts are made with two such bands. Thus a dimensional orientation of ice sub-parallel to the already established sediment surface results.

(c) Gaseous Inclusions

Bubble coalescence as a measure of deformation in ice sheets was given theoretical consideration by Weertman (1968); this is not applicable in the dead ice under study. Gow (1968, p. 181) found that bubbles in Antarctic glacier ice showed no tendency to be swept towards grain boundaries during recrystallization of the ice. Langway (1970, p. 28) mentioned the tendency for bubbles to "become smaller, more

spherical, and more uniformly distributed (spatially) with depth" in a deep ice core from Greenland.

Observations in situ

An indication of two-dimensional crystal shape was obtained from a study of etched grain boundaries on the tunnel walls (Plate 5). The results of a pencil rubbing are shown in Fig. 19. General relationships among the factors of inferred ice flow direction, sediment layers and grain size, elongation and intercrystalline junctions are evident.

Thin-Section Analysis

For more quantitative knowledge of these relationships, thin sections were analysed for the above-mentioned characteristics, while optic axis orientations were measured. Sections were photographed to provide slides from which triple-point angles and crystal size were measured, giving a greater degree of accuracy than is possible with direct readings from the section.

Texture Types

Several different characteristic textures were found.

(a) Sediment-Free Ice

1. Texture Type 1a

Remnants of an early texture are seen in the form of large (1-2 cm^2) crystals which were larger than at

present but suffered recrystallization, with the growth of small crystals. These large crystals show undulatory extinction and deformation bands; irregularly curved undulatory extinction indicates crystal bending. Deformation bands show all stages of development, from incipient to well-defined; in the latter case individual bands have extinction angles varying by as much as 10°, and are separated by approximately straight line sub-boundaries (Fig. 20).

Superimposed on the above texture is a recrystallization texture. As shown in Fig. 20, zones of fine-grained mosaics surround and embay the large non-recrystallized grains. Elsewhere, strings of fine grains traverse the larger, which retain their early deformational features. There is no evidence of strain within the finer grains, they are approximately equigranular, and their boundaries meet at close to 120° at triple points. Embayment of early large grains by small grains is concentrated at the aforementioned inter-deformation band boundaries again at 120°. That the smaller grains grew later than the larger is shown by the occurrence of unstrained fine crystals traversing large grains; thus the texture is due to recrystallization, and not to original porphyritic grain growth. Had deformation occurred after grain growth, small crystals would show some strain; deformation band boundaries would be independent of triple points. Recovery from plastic deformation is thus indicated, recrystallization occurring in the solid state. As pointed out above recrystal-

lization tends to reduce the surface free energy, and recovery absorbs the strain energy, thus there is a tendency towards thermodynamic equilibrium. The failure to reach complete equilibrium is indicated by departure from the 120° angle in some cases, although the frequency distribution of 800 grain boundary angles is unimodal and symmetrical about a peak at 120° (Fig. 21). Further evidence is the existence of curved grain boundaries. Such curved boundaries occur mainly in the large crystals, where individual bands act as single grains, both at indentations and at projections.

Thus in summary, Texture Type 1a shows that deformation banding was produced prior to recovery and annealing recrystallization, and thus is associated with the deformation. Measurement of c-axes of the grains indicated the effect on fabric diagrams of the recrystallization process. Referring to the optic axis diagrams discussed previously, it was found that small grains change orientation progressively with distance away from the larger relict crystals. Those nearest the relicts show orientation close to that of the original crystal; rotation increases with distance, thus explaining new orientations in the optic axis diagrams.

2. Texture Type 2a

A second texture type is shown in Fig. 22. This is termed strain-induced boundary migration, in which strained grains form nuclei from which unstrained outgrowths

project into adjacent grains. The absence of strain in the outgrowth shows that the migration is post-deformational, the process using the energy of the strained lattice. The shape of such outgrowths is often curved, where migration occurs away from the centre of curvature, elsewhere, straight parts of otherwise serrated boundaries indicate the existence of a crystallographic plane. Intense suturing is evidence for local strain inhomogeneities, these occurring in those crystals with optic axes far from the preferred orientation.

A given grain may display sutured, straight and curved parts to its boundary, depending on the relative lattice orientation of its neighbours. Mobility of a particular boundary segment is reduced between grains of similar orientation.

(b) Effect of Sediment

Sediment occurs in discrete bands, and as a dispersed phase. Considering firstly the dispersed grains, the sediment content in such layers is show in table 2. Linear traverses of slides, random samples, and tracing of grain boundaries showed no significant tendency for sediment to be found within grains rather than at boundaries, or vice versa, thus there is no control on ice crystal shape.

3. Texture Type 1b

Sediment bands had a definite effect on texture. As pointed out above, such bands effectively pin down moving ice-ice boundaries, ice crystals becoming elongated parallel

to the band. Compared with ice-ice interfaces, the interfacial tension of ice with a sediment band is very high, so the ice-ice boundaries trend normal to the sediment band.

Within these dirt layers, ice crystals were characteristically less than 1 mm in diameter. Due to the difficulty of melting evenly between sediment grains, the shape of the small crystals was not readily evident, nor was the optic axis orientation easily measured.

4. Texture Type 2b

Mimetic Growth

A more extreme type of grain growth is exhibited in the Style 3 Fold (Fig. 16). Here the post-folding grain growth has produced grain shapes mimetic of the sediment-ice foliation. Thus the syntectonic crystallization texture has been overprinted by later growth, in which strain energy of the lattice is reduced. Thus the post-tectonic crystallization is analogous to the process of annealing already described.

Mode of deformation and recrystallization as indicated by crystal shape

Four major texture types have been found, two associated with sediment-free ice, and two with sediment concentrations. In the sediment-free bands, some relict crystals show evidence of bending, these crystals having been in orientations which could not accommodate the imposed stress by slip on basal

planes. Other crystals rotated into orientations favourable for such slip and became extended parallel to the basal plane. The bent crystals have become embayed by smaller, strain-free grains which grew in a stage of recrystallization. Recrystallization also occurred in rotated crystals, leading to sutured grain boundaries through mutual intergrowth of adjacent grains. It is probable that where adjacent grains were of similar orientation, the dividing grain boundary disappeared to give one large grain. There is no evidence for this other than the presence of large grains which show slight variations in extinction angle without any indication of internal strain.

A contrasting texture is found in the Style 3 Fold, i.e., mimetic growth. In this case the fabric diagrams show a girdle at right angles to the general fold axis, and are homogeneous throughout the fold. Both the relict-type and sutured grain boundaries are absent, the grains having grown post-deformationally parallel to the bedding foliation. Thus there has arisen no optic or dimensional preferred orientation associated with slip parallel to the axial surfaces of the Style 1 Folds. The optic axis distribution indicates an early stage of deformation. Any strain energy was used in mimetic recrystallization.

The remaining texture type is a function of relative properties of ice and icy sediment, grain shape indicating that interfacial tensions between ice and sediment is greater

than at ice-ice boundaries.

The inferred deformational pattern is that an early stage of folding occurred in which no major grain shape pattern was developed. The Style 3 Fold is a relict from this stage, mimetic recrystallization having since occurred. Elsewhere, the fold form was modified by a flattening process, giving rise to a dimensional orientation of grains, parallel to the slip surface of the body. Superimposed on this orientation are recrystallization textures of sutured grain boundaries and relict bent grains. This mode of deformation agrees with that inferred from mesoscopic fold form and from optic axis orientations.

C. ICE GRAIN SIZE

Introduction

The presence of mimetic crystals such as those in Fig. 16 indicates the problems of making useful measurements of grain size. The mimetic crystals contrast markedly with the elongated shapes between sediment bands and those elsewhere with long axes parallel to the flow direction.

Problems

It is evident from the above discussion of grain shape characteristics that the size of a given crystal seen in section will have varied with time. Measurements of crystal

area give only an estimate of the two-dimensional size of three-dimensional objects which have not necessarily reached equilibrium. The irregularities of grain shape make estimates of volume of little value. Using three mutually perpendicular sections at a given sampling point it was possible to study any tendency for elongate shape produced during flow, or due to the presence of sediment bands. Sections were photographed on a measured grid and slides projected on to gridded paper to make areal measurements of greater accuracy than is possible directly on the Universal Stage.

In addition to the problems outlined above, a given section through a sphere, say, will rarely give a maximal sectional area. The problems are multiplied in an aggregate of variously sized and shaped particles, and where inclusions give rise to marked changes in grain size.

Results

It is found from the literature that Östrem (1963) and Taylor (1962) gave estimates of grain size based on measurements of long and short axes. Axis lengths were multiplied together and averaged for 100 grains. For comparison with published results, the present author measured area and long and short axis length from projected photographic slides. The results are plotted in Table 1.

From inspection of the table it can be seen that areas measured in horizontal sections are greater than those from

vertical sections, as would be expected due to elongation parallel to flow. This was seen in vertical sections at right angles to the fold axis. But it is also noted that the horizontal sections in the second fold show markedly different grain sizes, 0.340 cm^2, 0.492 cm^2 due to the presence of a sediment band, as discussed in the section concerning optic axis orientation. These sections were prepared to show the influence of such sediment. In summary, only the general conclusion can be made that three-dimensional shapes of ice crystals in the ice body display a strong tendency for elongation parallel to the axial surface, longest axes being in the flow direction. Locally sediment bands control ice grain size within those bands, and enhance the dimensional orientation in adjacent ice crystals. As is the case in metamorphic petrology in general, no method is available for the estimation of grain size of such irregularly shaped materials. In less deformed material the more equant shapes lend themselves to comparison with standard circles for areal measurements.

D. SEDIMENT

(a) Sediment Grain Size

Samples were taken from the positions shown in Fig. 23 for which the grain size distributions are plotted in Fig. 24, on the basis of the results of sieving. As the lenses and boudins contain sedimentary structures, samples

from them must contain grains from more than one layer. However, the cumulative distribution curves show no pronounced "kick", Fig. 24. Cross bedding structures are present in the study area and are similar to those found in fluvial sands found in the Tuktoyaktuk area (Rampton 1970, 1971).

(b) Sediment Content Analysis

From figures of folds and thin sections it is evident that sediment content varies greatly. Amounts of debris in a thin section are insufficient to estimate dirt content by an areal measurement. Thus a series of blocks was cut in a vertical line from the core of the "First Style 1 Fold" of the structure analysis, see Fig. 23 and Table 2. The number of samples is insufficient to make any conclusion other than that a wide variety of sediment contents exists. A value of 80% excess ice by total volume was found by Rampton and Mackay (1971, p. 8) on the basis of a vertical channel sample. Due to the complex folding, it is likely that a bed may have been sampled more than once in that sample.

TABLE 1

Sample		Section Orientation	Average size cm^2	Average long, short axis cm	Number Crystals
Fold 1	Block 1	Horizontal	0.508	0.8x0.6	100
		Vertical parallel axis	0.343	0.6x0.5	150
	Block 2	Horizontal	0.76	0.9x0.8	90
		Vertical parallel axis	0.84	1.0x0.8	80
		Vertical perpendicular to axis	0.55	0.9x0.6	100
	Block 3	Horizontal	0.587	0.8x0.7	215
		Vertical parallel axis	0.432	0.8x0.5	95
	Block 4	Horizontal	0.514	0.8x0.7	80
	Block 5	Horizontal	0.752	1.0x0.7	80
Fold 2		Horizontal	0.340	0.6x0.6	106
		Horizontal	0.492	0.7x0.7	105
		Vertical parallel axis	0.307	0.6x0.5	100

TABLE 2

Samples from this study

		Sediment as % Total Weight	
	Site	Sample 1	Sample 2
First Style 1 Fold	(a)	3.25	4.19
	(b)	23.31	24.38
	(c)	10.97	8.35
	(d)	9.18	6.77
	(e)	24.16	20.53
	(f)	41.32	38.64
Second Style 1 Fold	(a)	12.31	8.52
	(b)	9.82	7.31
	(c)	4.11	4.23

The two measurements for each bed indicate within sample variation from close samples for a given bed.

E. WATER QUALITY ANALYSIS

Rampton (personal communication, 1973) provided the results of water quality together with those for ice from other bodies in the Tuktoyaktuk area.

TABLE 3

Analysis (Milligrams per Litre)

	Ice Cellar			Nearby Pingo		Slump Face in Involuted Hill near Tuktoyaktuk
	1	2	3	1	2	
CO_2	5.7	4.4		2.7	1.2	12.3
Alkalinity ($CaCO_3$)	117	143	75.3	111	10.0	0.0
Spec. Conductance	268	463	157	269	44.1	40.5
Hardness (Total)	132	247	83.8	135	17.1	18.0
As $CaCO_3$ (non-carbonate)	15.0	104		24.0	7.1	2.1
Ca	48.7	93.8	8.1	49.6	5.7	5.4
Mg	2.5	3.1		2.7	0.7	1.1
Na	3.4	4.4	0.3	1.7	0.7	0.4
K	2.8	2.9	0.6	1.7	0.6	0.1
HCO_3	143	174		135.0	12.2	19.4
SO_4	12.4	96.2		23.3	2.7	2.3
Cl	5.4	5.5	0.8	2.3	1.0	0.8
N	3.1	4.2	0.07	1.5		0.29
SiO_2	1.7	3.2	1.5	2.4	0.4	0.00

Thus there exists wide variation among the three samples from the cellar. The two most similar samples are Cellar sample 1 and the Pingo sample 1. In comparison with tabulated values for samples from present-day glaciers and ice-sheets (Langway 1970) all the Tuktoyaktuk samples differ in having a very much higher chemical content. Thus it may be concluded that the place of origin of the deformed beds was not the upper part of a glacier. Considering ice origin at the base of an ice-sheet terminus, water sources would be local ground water, precipitation and ice meltwater. The similarity between ice cellar water quality and that of pingo ice recently frozen indicates that if the cellar ice is of glacier origin, dilution of ground water by meltwater and precipitation was small.

CHAPTER VI

CONCLUSION

The discussion in this paper shows that the folded underground ice in Tuktoyaktuk, N.W.T. has been subject to progressive deformation. Several stages of folding have been distinguished, the microscopic and mesoscopic features being related by their symmetry. A change in direction of the major stress axis has been inferred. Such are the inferences from study of the limited available exposure. There remain the problems of: (a) determining the origin of the ice-icy sediment sequence; (b) determining whether deformation occurred as part of an ice sheet or by overriding of ground ice by an ice sheet.

(a) Origin of the bedding sequence

Several possible mechanisms exist:

(i) Freezing, from above, of fluvial sands with sedimentary structures.

(ii) the unfrozen sediment was incorporated into the bottom of an ice sheet:

(a) sediment was part of the ice sheet bed, at some distance from the snout, and was frozen on to the ice sheet, the water being local ground-

water, or subglacial meltwater from up glacier.
(b) sediment was transported to the base of the ice sheet by subglacial water near the ice sheet margin. The water and sediment would be of several origins; water from precipitation, melt at the ice snout, melt from upglacier, each type supplying sediment.

(iii) wind- or water-deposited sediment higher on the ice sheet or glacier.

(iv) river, lake or sea ice with a periodic supply of wind blown sand.

Examination of mechanisms

Mechanism (iii) is rejected, on the grounds that (a) water quality analysis shows chemical content of water from the Tuktoyaktuk ice to be significantly different from those for glacier ice reported by Langway (1970), and that (b) ice of such an origin could not suffer the deformation displayed.

Mechanism (iv) is rejected on the grounds that (a) wind blown sand is not of sufficient quantity under the conditions of ice cover active today to give the rhythmic bedding shown, (b) the mechanism requires freezing upwards; water supply would be insufficient to give the ice thickness shown, and (c) water quality is atypical of such ice.

There remain mechanisms (i), (iia), (iib). Considering mechanism (i), water quality analysis of the folded ice shows

more similarity to that of nearby pingos, which are thought to have grown by segregation of ground ice, than to upper parts of present day ice sheets. This applies also in the case of subglacially entrained sediment, where some of the water is of subterranean origin. But a distinction is made in mechanism (ii), based on distance from the ice sheet margin. Because of overburden pressures, sediment below an ice sheet cannot have ice in its pores unless there is a mechanism of pressure release. Such release cannot occur at great distances from the snout, thus mechanism (iia) is rejected. Mechanism (iib) is retained, as near the snout subglacial channels occur, also pressure may be released through the bed. This mechanism requires burial of the deformed ice by sand and gravel, without total melting.

The narrow grain size range must be explained. The preglaciation history of the area is poorly understood, but the distribution of various sediment types is being mapped, sands underlying much of the area as far east as Nicholson Peninsula. The grain size can be explained by both mechanism (i) and (iib). If the pre-freezing sediment is of wind or water transportation, by analogy with present freezing processes the grain size distribution would not be altered as a freezing front penetrated as in mechanism (i). Similarly in "freezing-on" called for by (iib). A further possibility exists in case (iib), where the glacier bed would be of a wide range of sediment size, but a grain size selective

incorporation occurs, as described by Souchez (1967). The presence of some pebbles complicates the issue. Also present are small wood fragments which are characteristic of the surrounding sands.

Thus, restricting the argument to the pre-deformational origin of the bedding, no conclusive distinction can be made between mechanisms (i) and (iib).

Thus consideration is given to the mode of deformation.

(b) Mode of deformation

Accepting that two alternative origins of the predeformational bedding exist, an attempt is made to distinguish them by criteria of mesoscopic and microscopic deformational form.

The two possibilities are (a) normally segregated ground ice later deformed by overriding glacier ice, (b) the ice is an ice-sheet remnant, in which case the deformation was internal.

The mesoscopic folds show axes trending approximately 130°; of the two possible directions of major transport, fold form indicates movement from approximately 220°. These directions are relative to magnetic North; after correction to geographic reference points, deformation is seen to be from a southerly direction. This would apply in both case (a) and case (b). This direction is in agreement with directions of ice movement inferred from other features in the area.

Separate examination of the two mechanisms is made.

Suggested Deformation Mechanism (a)

The stress system operative during overriding of ground ice by an active ice-sheet is considered. Mackay and Stager (1966) described tilted beds of segregated ice in the Mackenzie Delta region. The stress system responsible was an advancing ice-sheet. The glacial geology literature contains many descriptions of folded sediments, the deformation being attributed to ice (de Sitter 1964, p. 329).

The stress system depends on the topographic form encountered by the advancing ice-sheet. At present, massive ice bodies form topographic uplifts, which would be subject to lateral compression and buckle folding. Such early formed folds would suffer overturning and extension in the flow direction as the obstruction was over-ridden, with differential flow in the different beds. Both open and tight folds occur in an ice-sediment sequence apparently continuous with undeformed material, on Pelly Island (Mackay 1973, personal communication).

Suggested Mechanism (b)

In this case, sediment accumulates in layers of varying concentration at the base of an ice sheet. These originally sub-parallel layers are then subject to folding within an actively deforming body, namely the terminal region of an ice sheet.

The stress system in such a body varies from place to place within the body, and over time. Shears occur, but between shears, active folding occurs, thus there is a compressive stress system. But above, both vertically and up-glacier, a zone of tension will exist, productive of crevasses.

In the basal compressive zone, first-formed folds are concentric, but become progressively more tightly appressed. Shears occur oblique to fold axial surfaces. Compression of beds with different rheological properties gives rise to boudinage-type structures. Extension of beds may lead to rootless folds. If the ice at Tuktoyaktuk is of such an origin it will have come from a position some distance up from the glacier bed, in order to explain the tightness of folds.

For ice of such an origin to have survived, two conditions must be satisfied (a) burial of the ice; (b) continued temperatures below the melting point of the ice.

Condition (a) could be satisfied by the production of a veneer of fluvio-glacial sand. Condition (b) is known to have been the case, as radiocarbon dates in the region indicate ice bodies to be of ages greater than pre-Classical Wisconsin.

Microscopic Structure

Deformation mechanism (a)

Petrofabrics of ice from such a body have not been discussed in the literature. It is suggested that early-formed folds would be flattened and extended, giving strong optic axis maxima orthogonal to axial surfaces, also preferred dimensional orientation parallel to the flow.

Deformation mechanism (b)

Intense internal modification is expected under the conditions suggested. Reports of field studies of present-day glacier and ice-sheet margins show strong crystal optic axis orientations to occur, also bending of crystals, and associated optic anomalies. Grain shape studies of active ice show some preferred dimensional orientation. Investigations of post-deformational recrystallization of strongly folded ice have not been reported.

Summary

Due to the lack of published results of field studies on the several ice types under conditions of active deformation, and before and after post-deformational recrystallization, no decision can be made concerning the deformation of the ice at Tuktoyaktuk. There is a great similarity between the ice at Tuktoyaktuk and folded ice in ice sheet margins.

Also the recrystallization textures can be explained on theoretical grounds. However, due to the lack of knowledge of properties of ground ice known to have been folded by an externally impressed stress system, this alternative remains. The origin of the sand-ice system is thus unknown, although the possibilities are reduced to two.

(c) Diagnostic petrographic features of the Tuktoyaktuk ice

One of the objectives of this study was to list diagnostic petrographic features of the ice for future field recognition from limited samples. Owing to the inconclusive knowledge of original ice growth and subsequent deformation the characteristics listed below will not be useful in attempts to distinguish the two types of deformation. It is hoped that the properties will be valuable in determining the areal extent and depth of the Tuktoyaktuk ice.

It is unlikely that core samples would yield fold closures, thus the summary concentrates on microscopic features. Relatively pure ice is considered separately from sediment-rich ice. Orientation of the foliation relative to the cover must be known.

(I) Pure ice

(i) Ice Grain shape

Grains have a dimensional preferred orientation in an approximately horizontal plane. Grain boundaries may be sutured, or be straight

with triple point angles tending to 120°, especially where relict strained grains are embayed.

(ii) Ice Grain size

Size ranges vary with grain shape type. Sutured grains are approximately 1.0 cm by 1.0 cm by 0.7 cm, although much larger grains occur. Relict strained grains are approximately 1.5 cm by 2.0 cm and are surrounded by smaller unstrained grains 0.7 cm by 0.5 cm.

(II) Ice with sediment bands

(i) Ice Grain shape

Grains are elongated parallel to the bedding foliation, grain boundaries meeting the sediment band at approximately 90°. Away from the sediment bands, shape is similar to that in category (a).

(ii) Ice grain size

Within sediment bands, ice crystals are limited to inter-sediment grain space size, many being less than 1 mm. Elsewhere, size corresponds to that in category (a), although few relict grains occur close to sediment bands.

(III) Optic axis orientation in ice and icy sediment

Optic axes show strong concentrations, of up to 20% per 1% area, in a vertical direction.

Minor variations occur, dependent on degree of recrystallization. Girdle patterns occur in a vertical plane for ice from a relict open fold.

(d) Suggestions for further work

The extent of the Tuktoyaktuk ice body is unknown, both areally and to depth. Knowledge of mesoscopic and microscopic characteristics at various depths would be helpful in determining the origin of the body. If evidence of deformation decreased with depth, this would be indicative of deformation by a superimposed stress system, rather than deformation within a tectonite.

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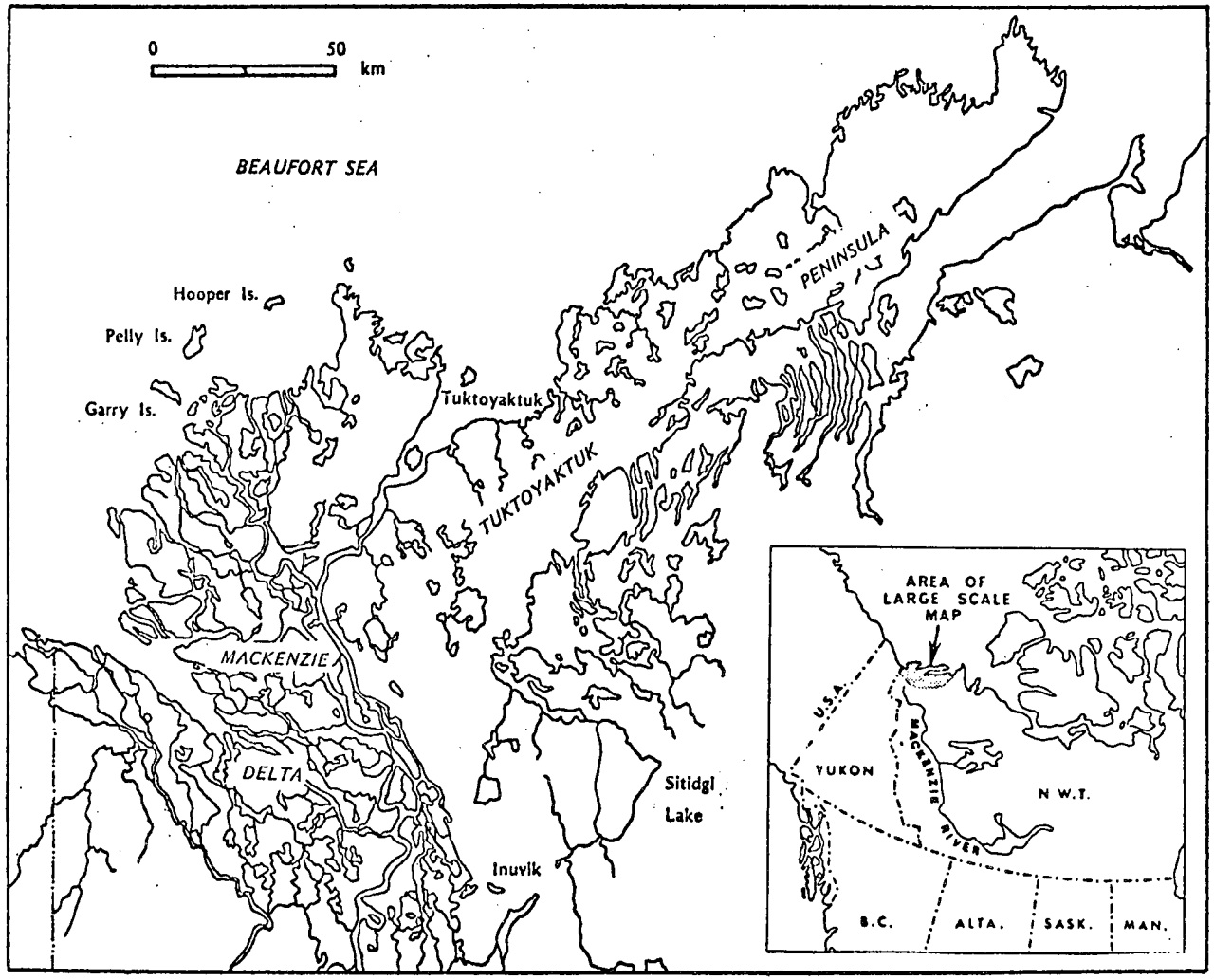


Figure 1. Location Map

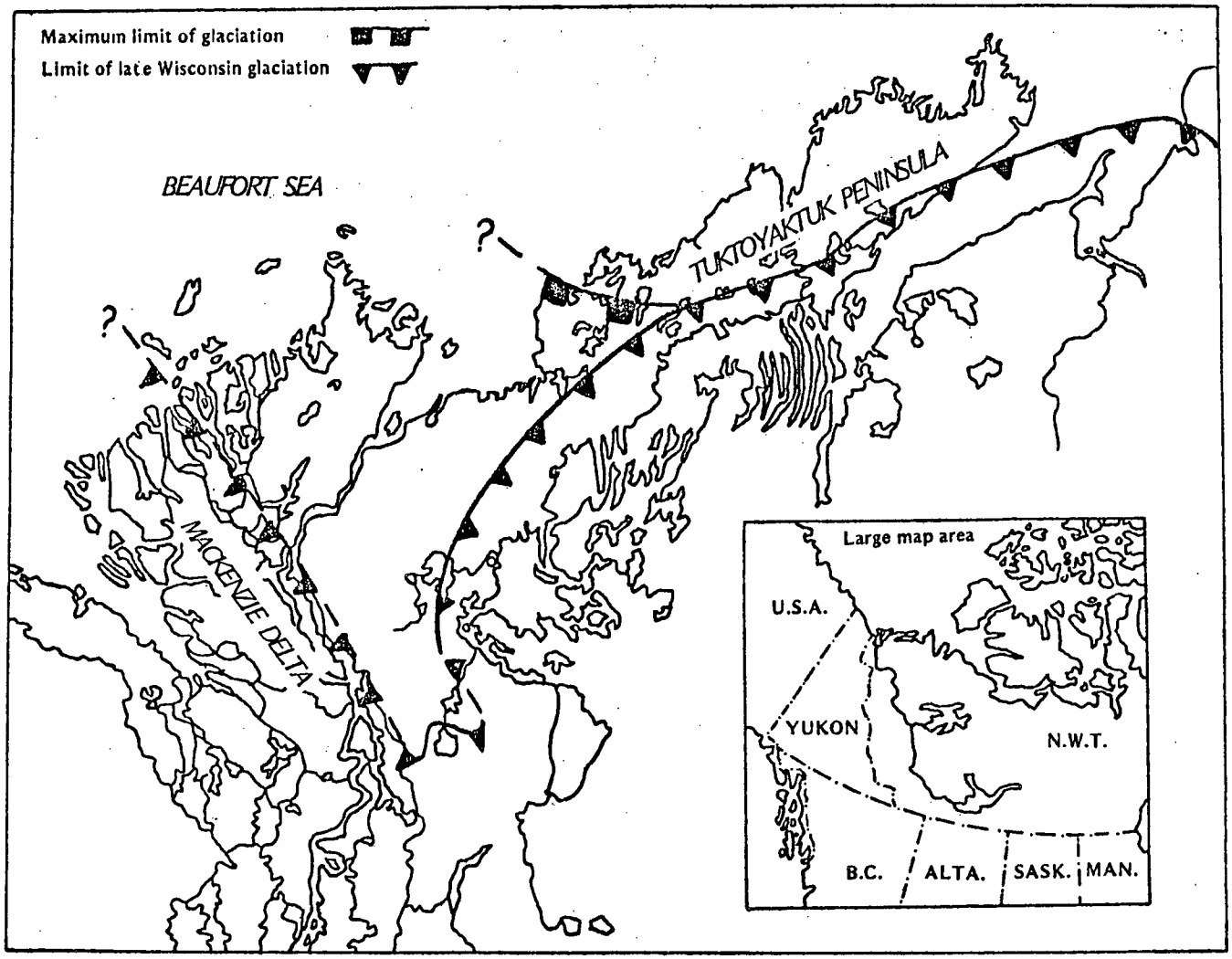
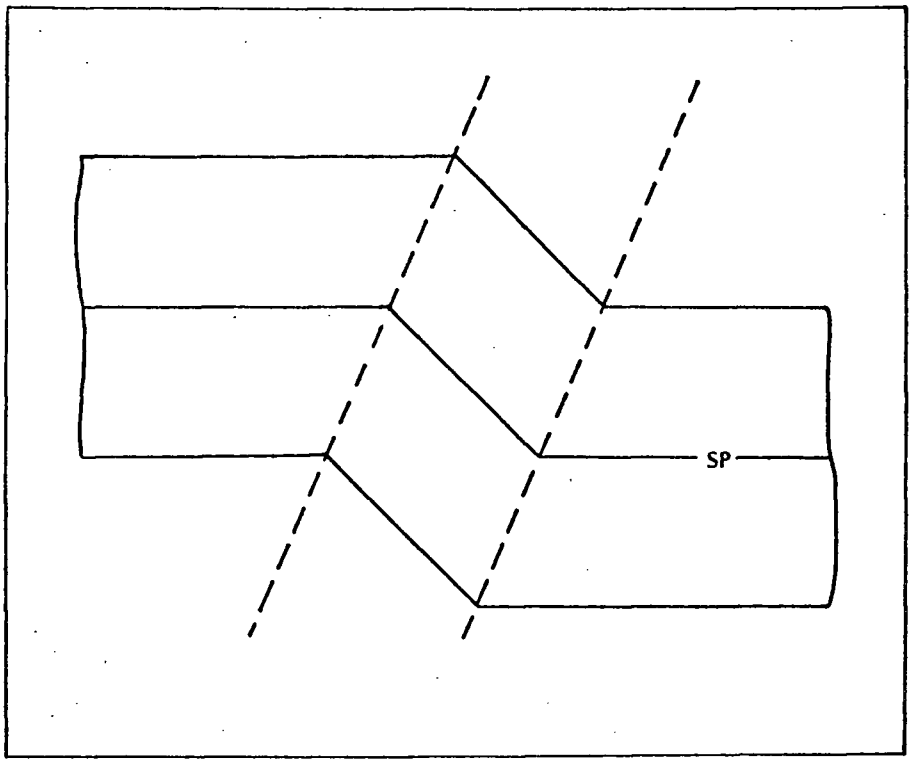


Figure 2. Maximum and late Wisconsin limits of glaciation

Figure 3a. Kink bank in a deformed crystal
SP = Slip plane



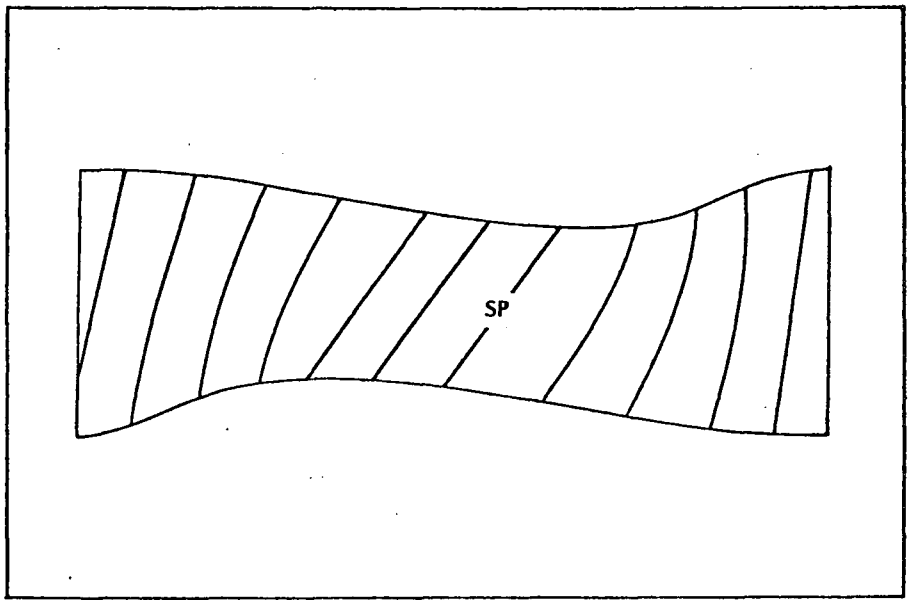


Figure 3b. Bending has produced a change in lattice and optical directions across the crystal. Undulatory extinction results.

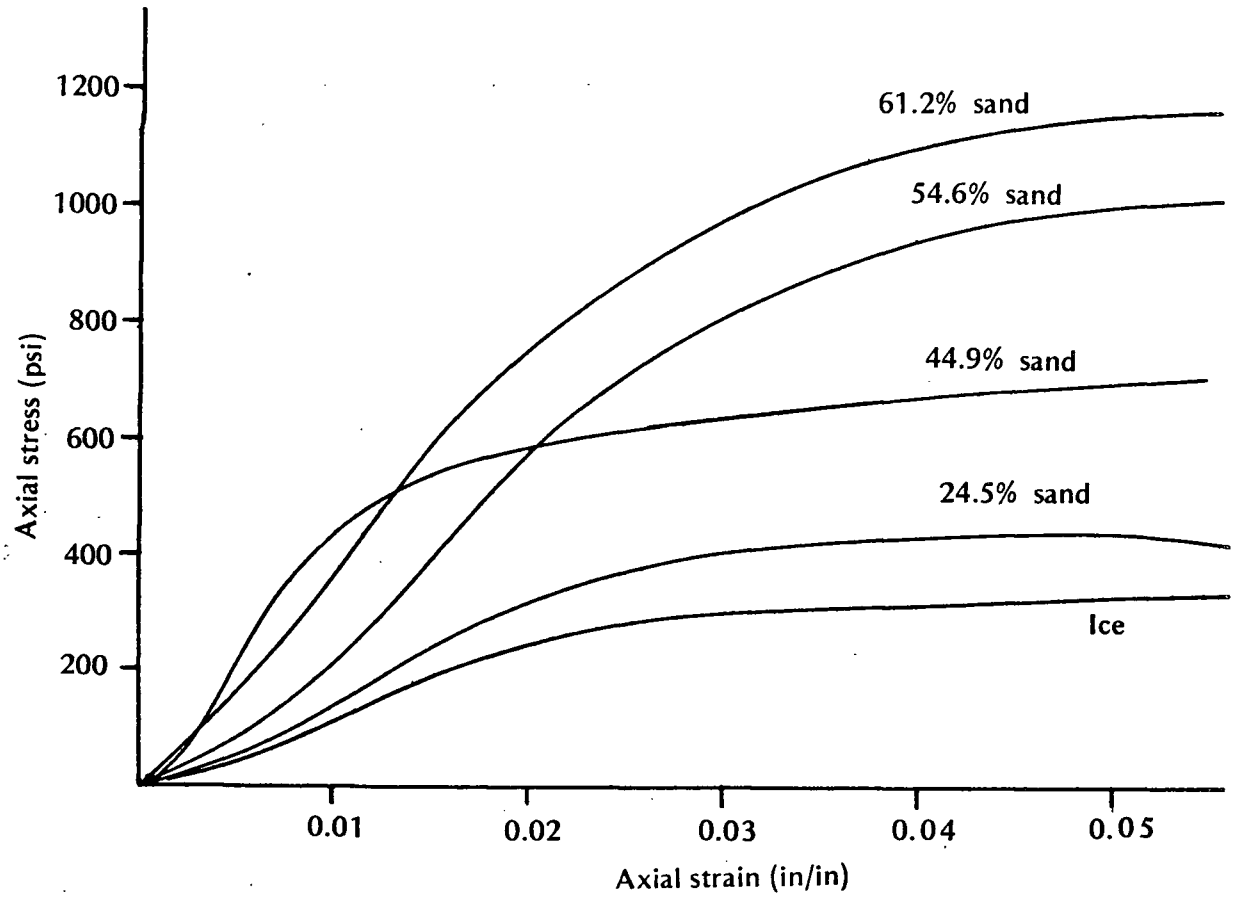


Figure 4. Stress-strain curves for pure ice and ice with varying sediment contents.
(after Goughnour and Andersland 1968).

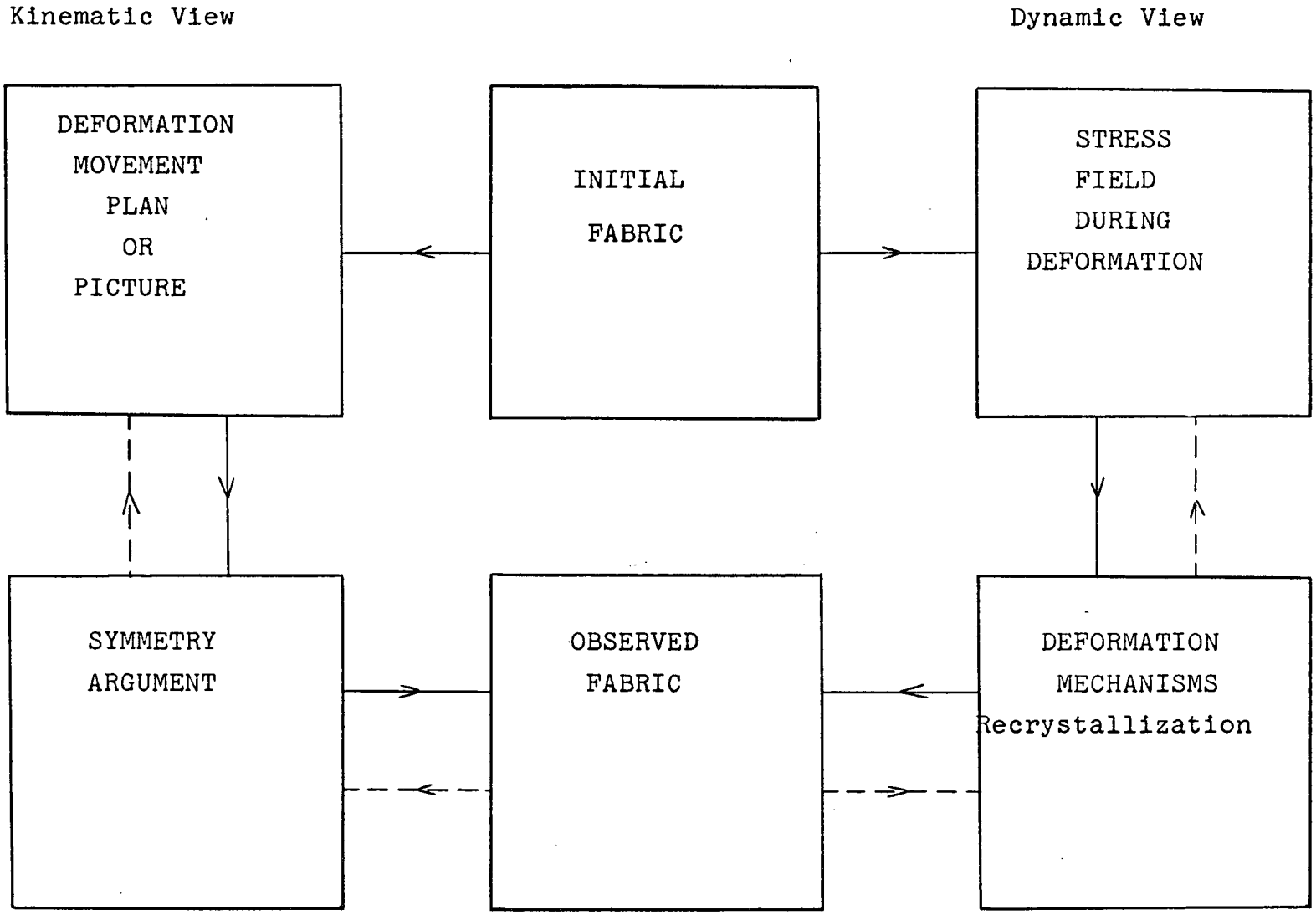


Figure 5. Dynamic and Kinematic viewpoints of Deformation

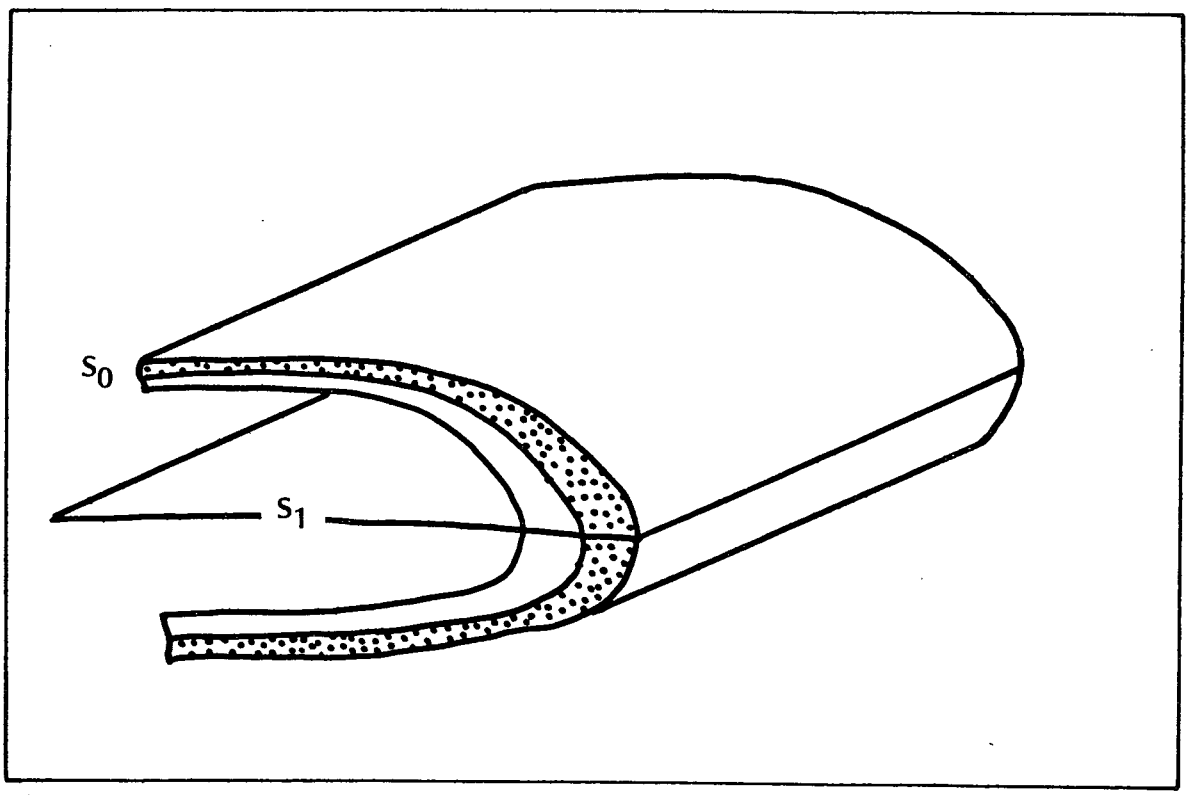


Figure 6. Relationship between S-surfaces
S_0 = original bedding
S_1 = axial surface of Fold

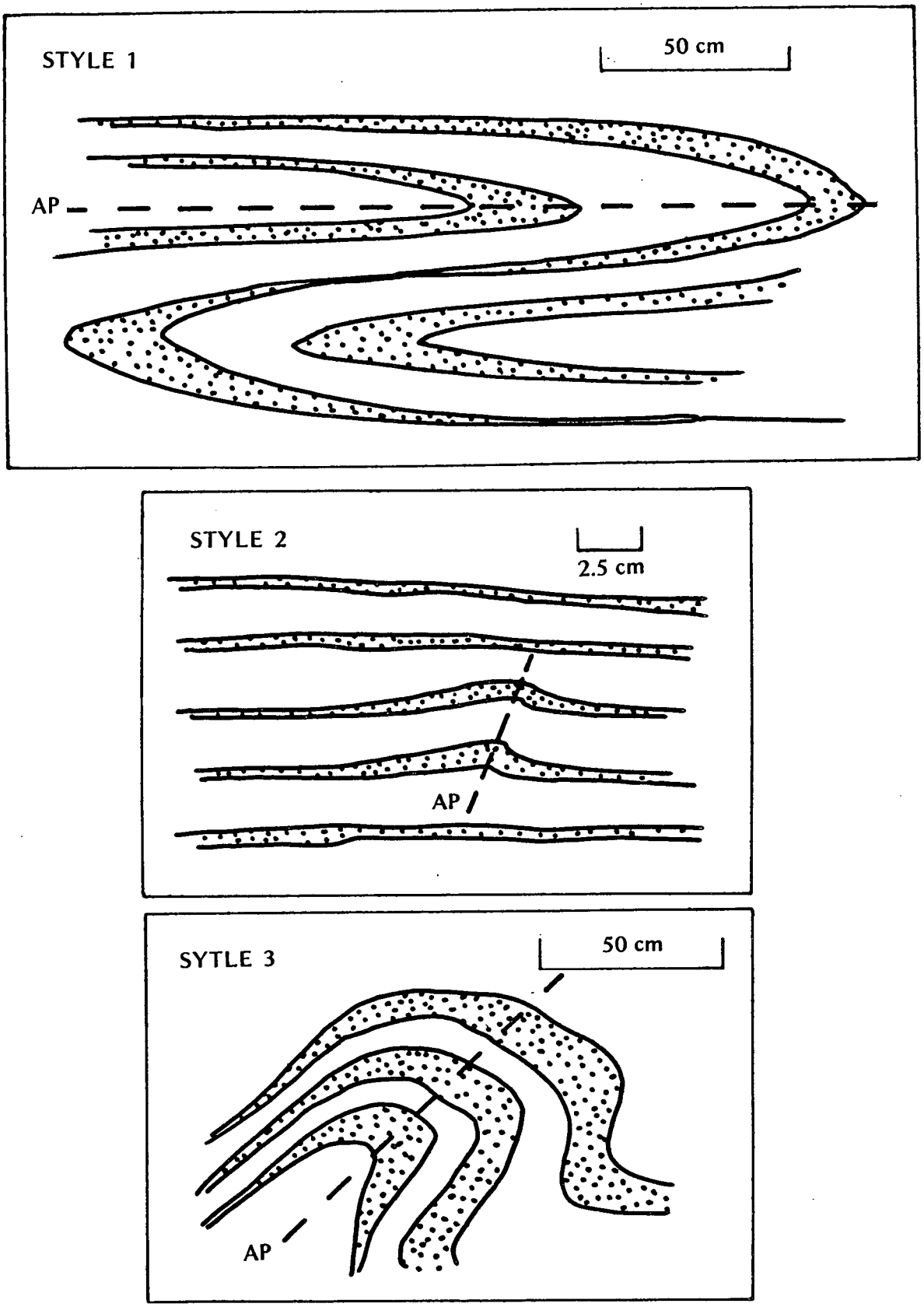


Figure 7. Fold Styles
AP = Axial Plane

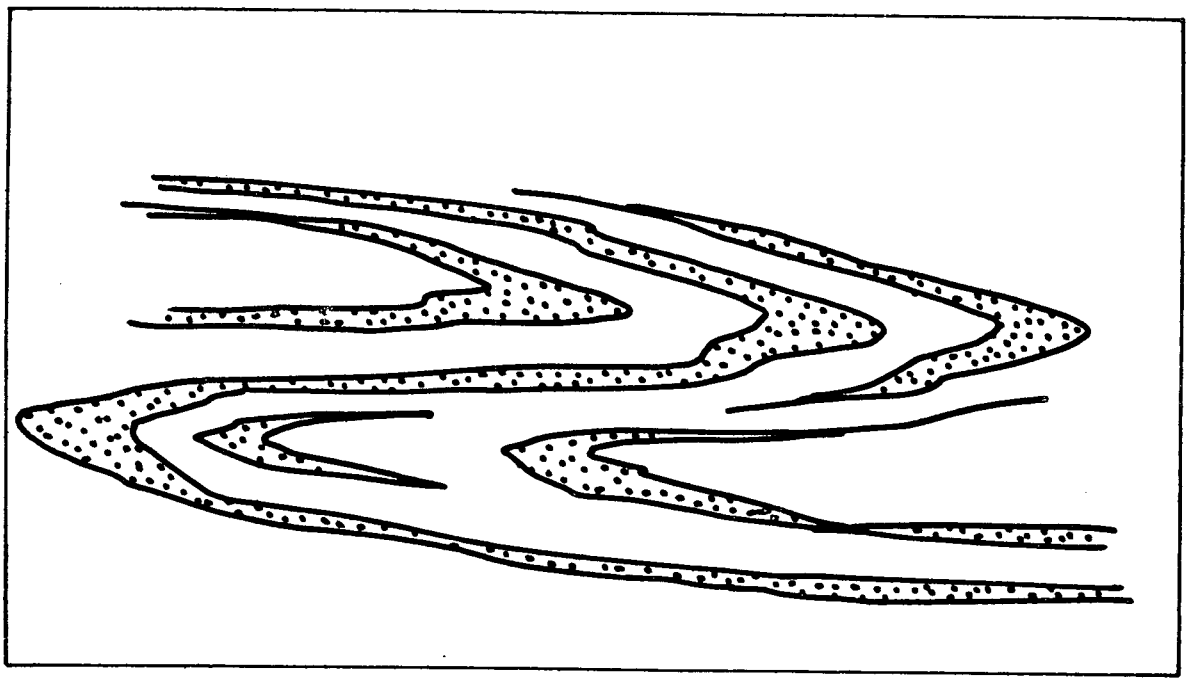


Figure 8. "Rootless folds" of Style 1.

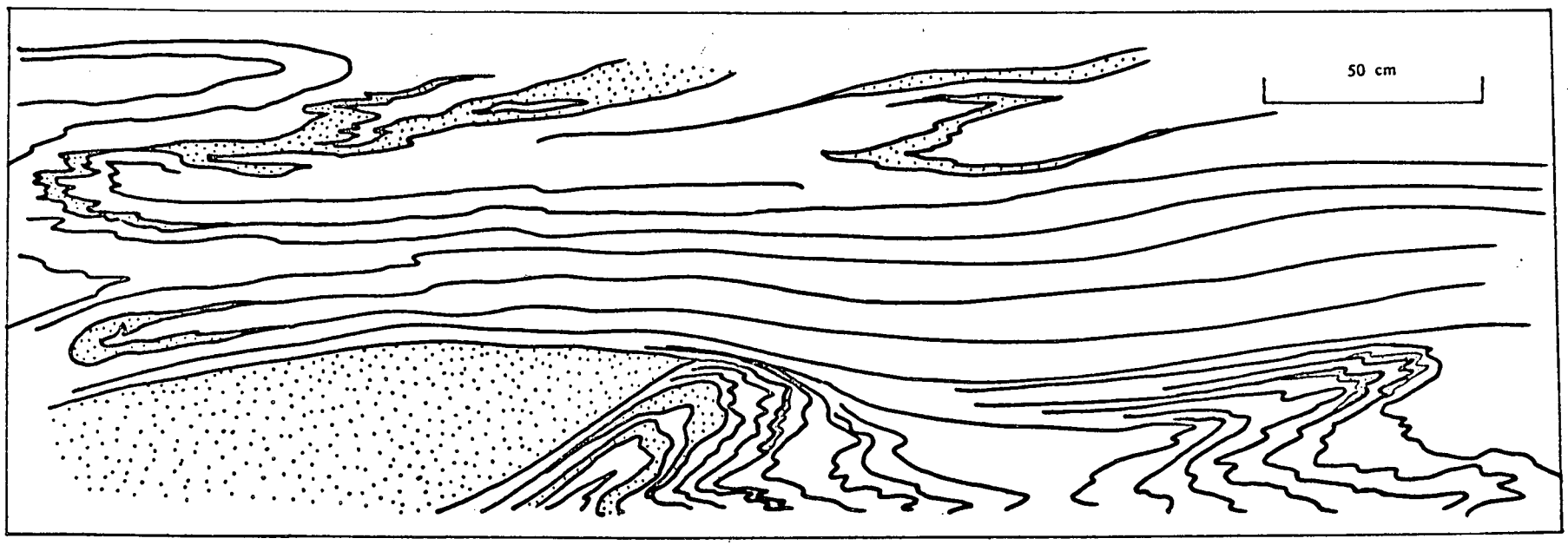


Figure 9. Style 3 Fold passing laterally and vertically into Style 1 Folds

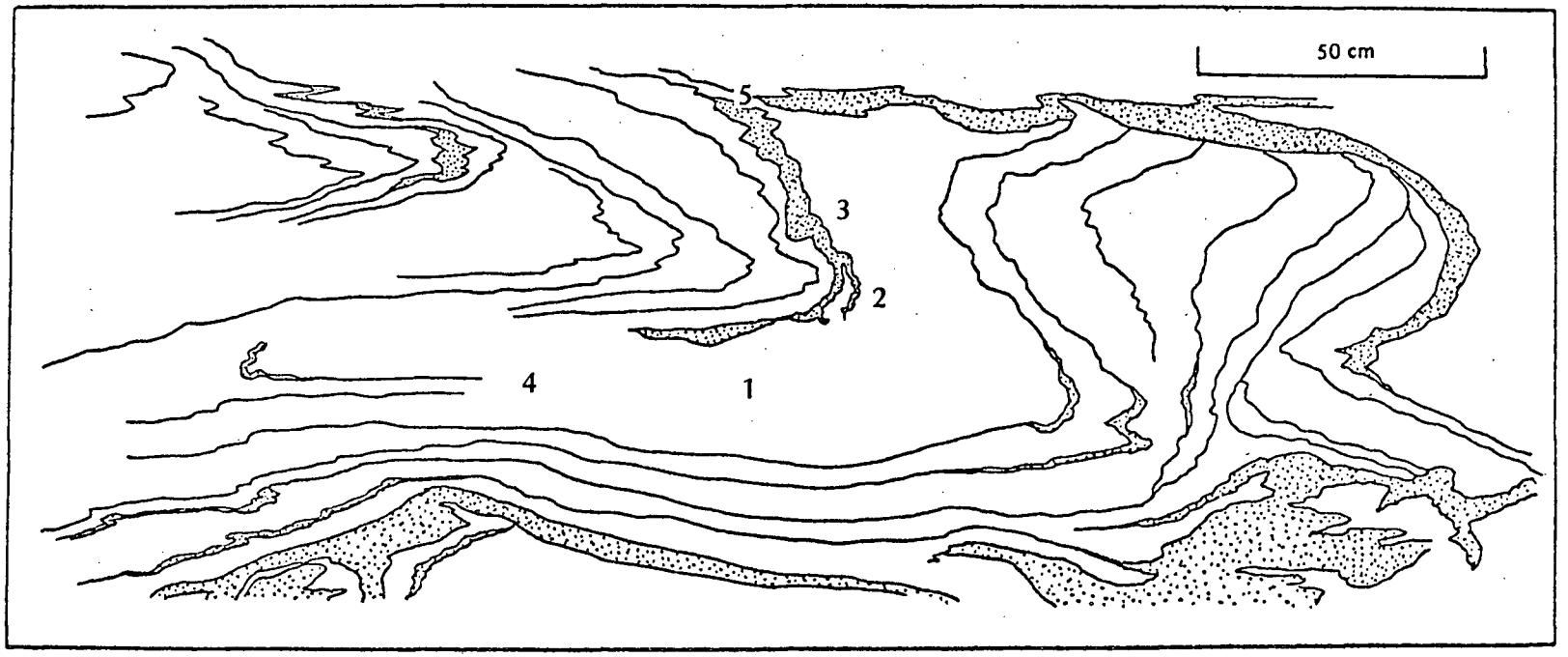


Figure 10. Sampling Stations for First Style 1 Fold.
1, 2, 3, 4, 5 are positions of blocks for thin sections analysis.

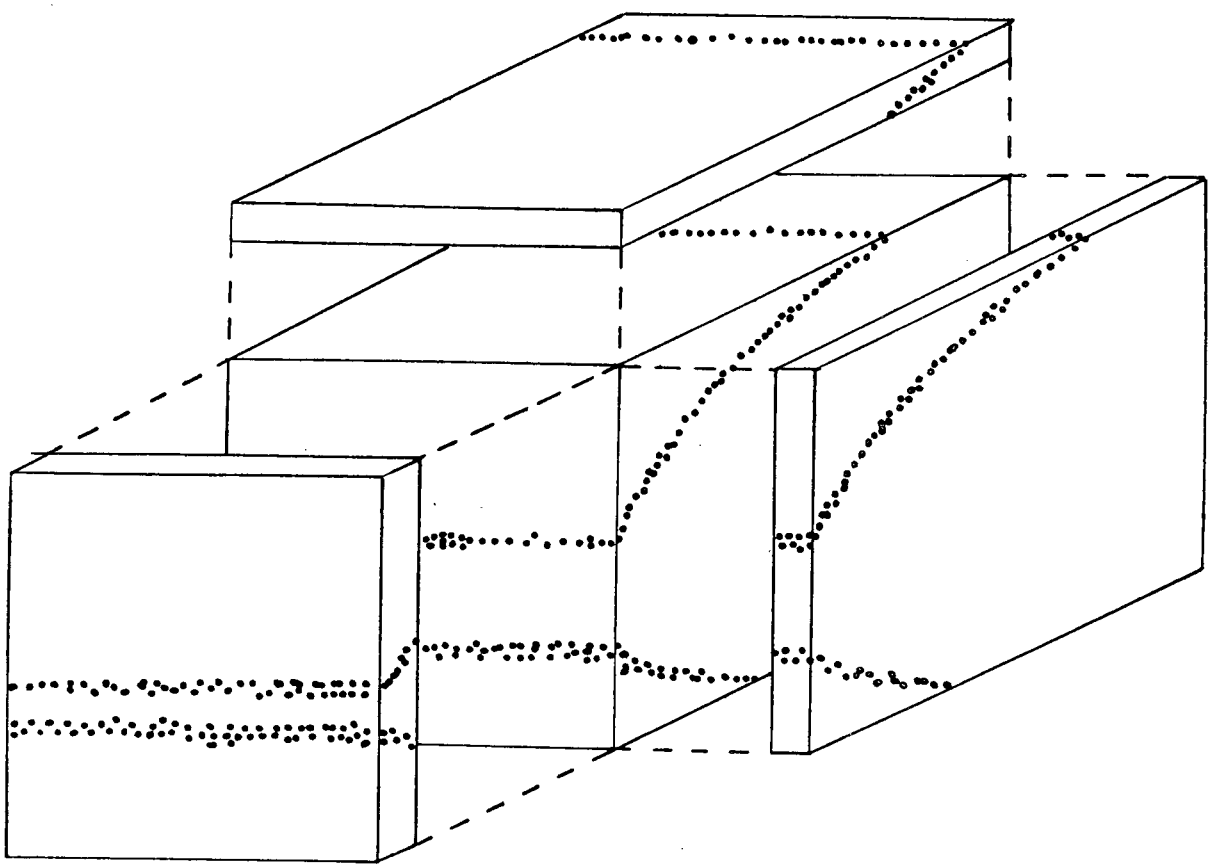
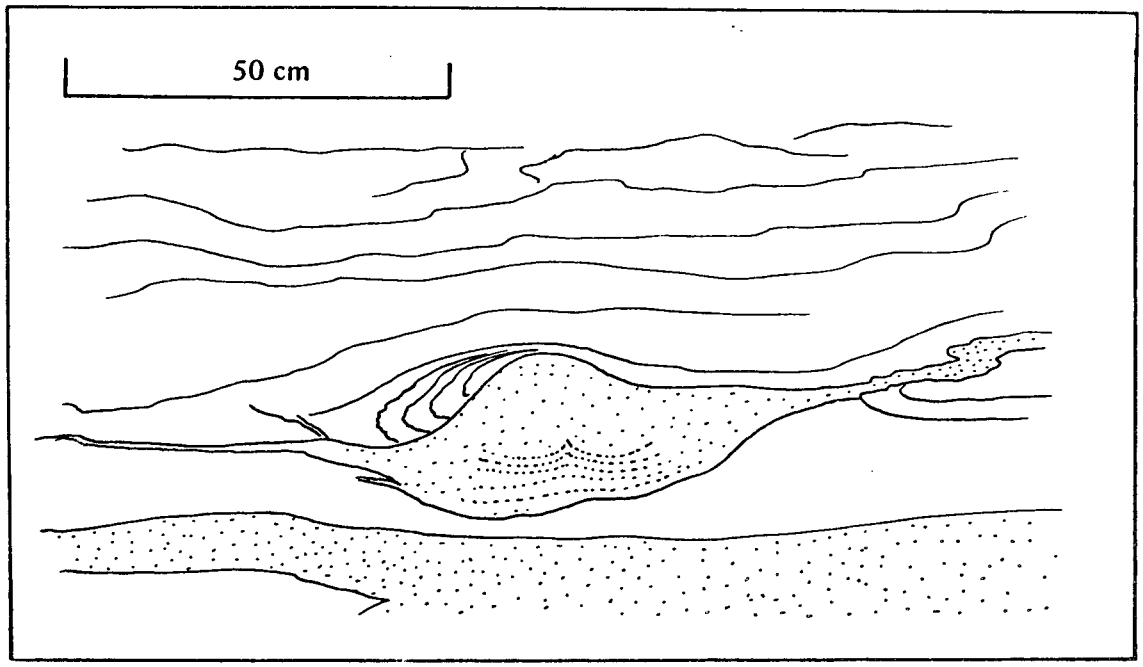


Figure 11. The Three Thin section Orientations



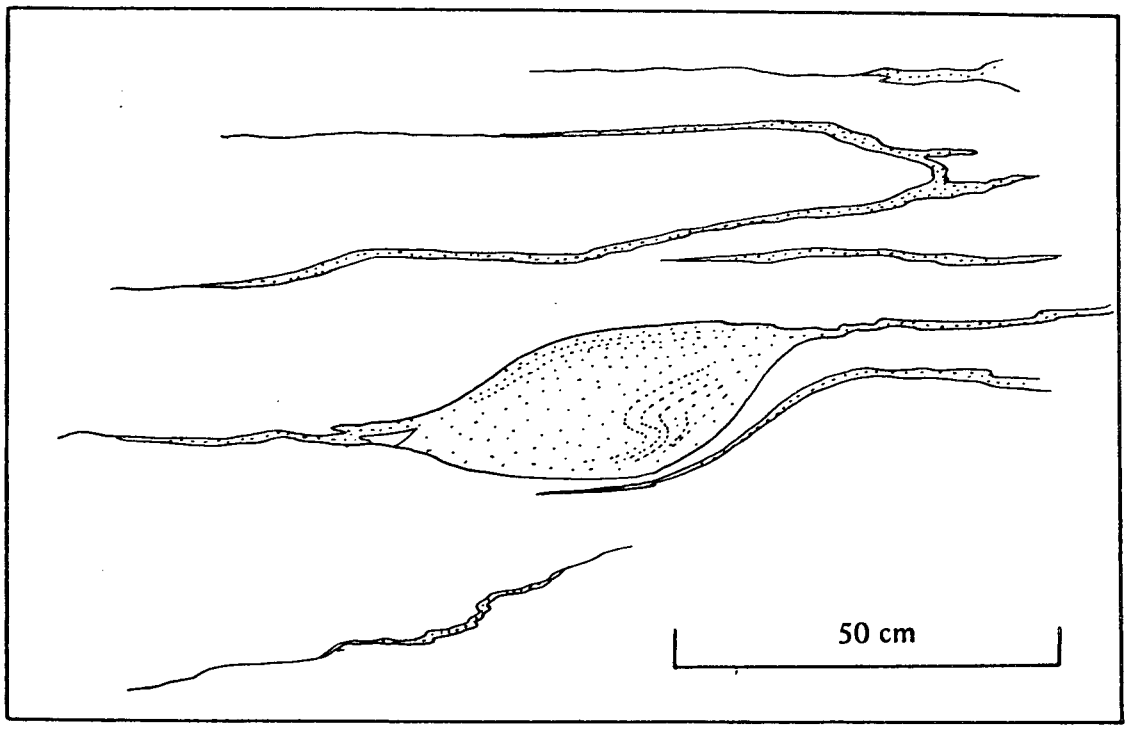


Figure 12 a, b. Boudinage of sandy ice within ice. Both boudins are rounded, (b) has S-shape.

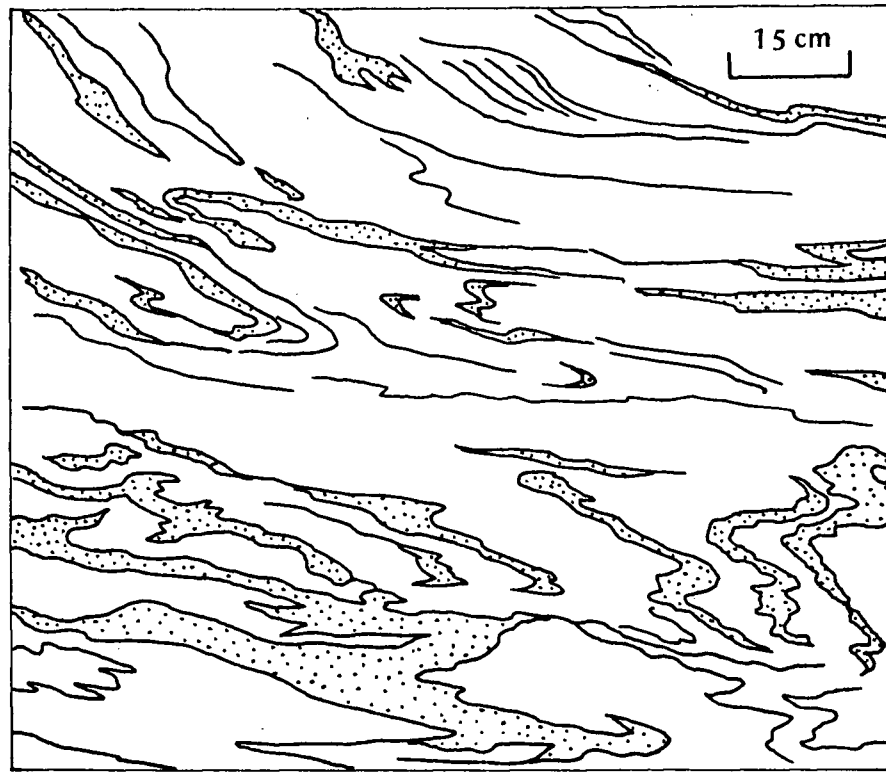


Figure 13. Transposition structures. Bedding foliation largely obliterated.

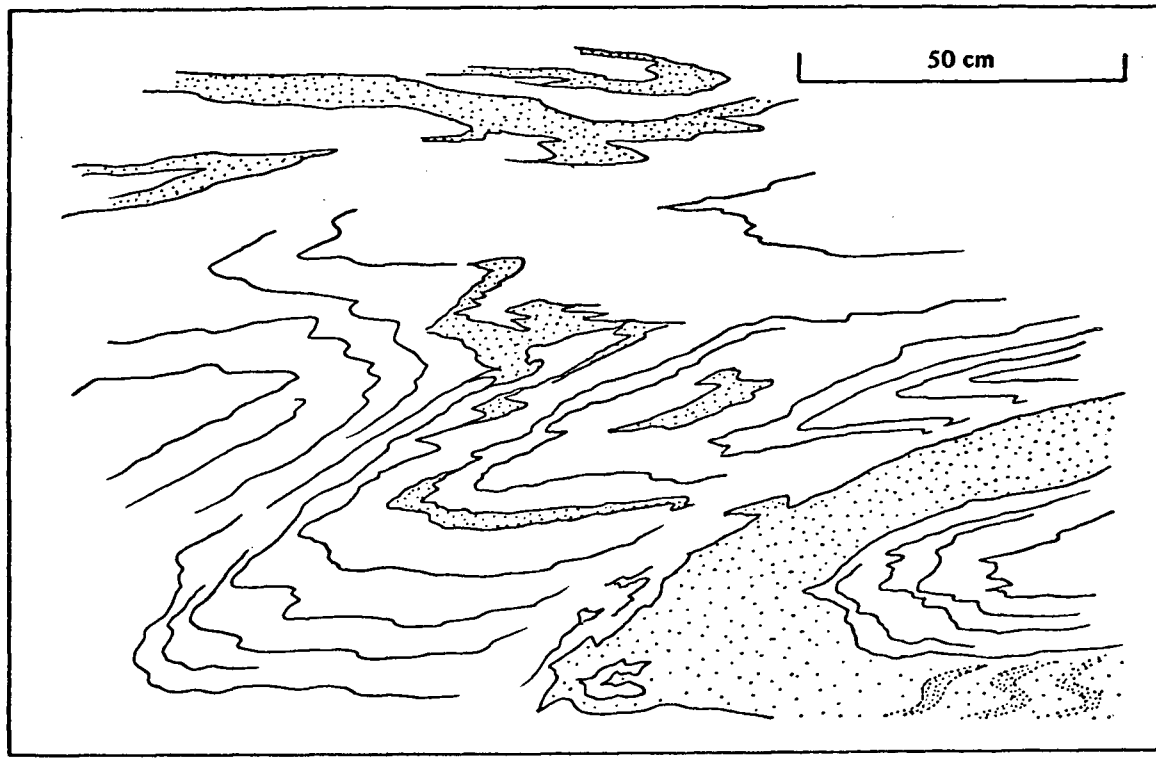


Figure 14. Shear indicated by juxtaposition of two synclines. Minor S-shaped structures occur within sediment band.

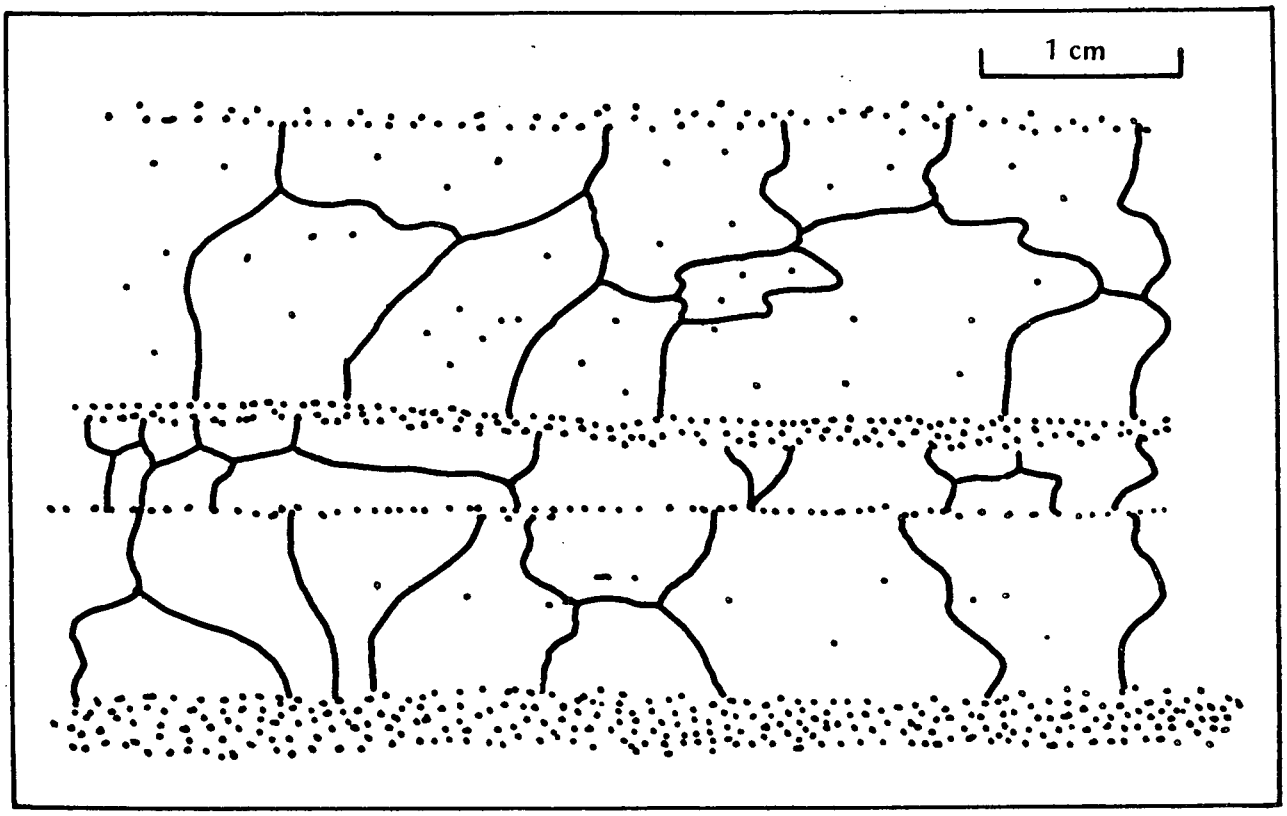


Figure 15. Effect of sediment on grain boundary shape.

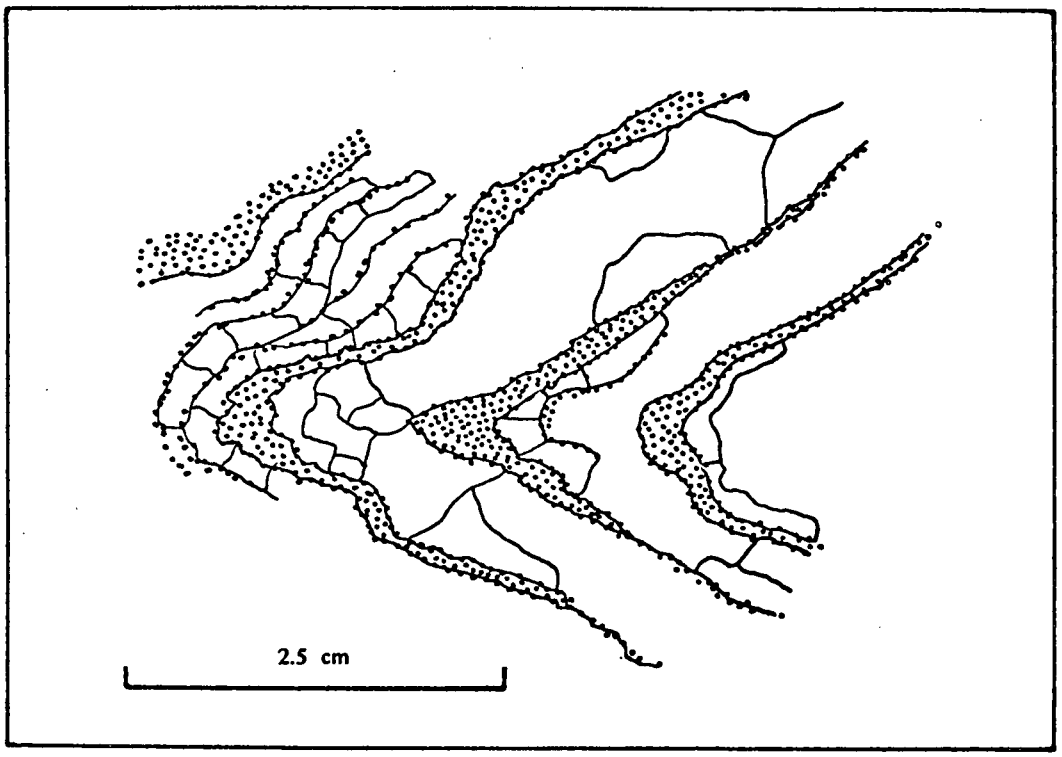


Figure 16. Mimetic post-deformational crystal growth in Style 3 fold.

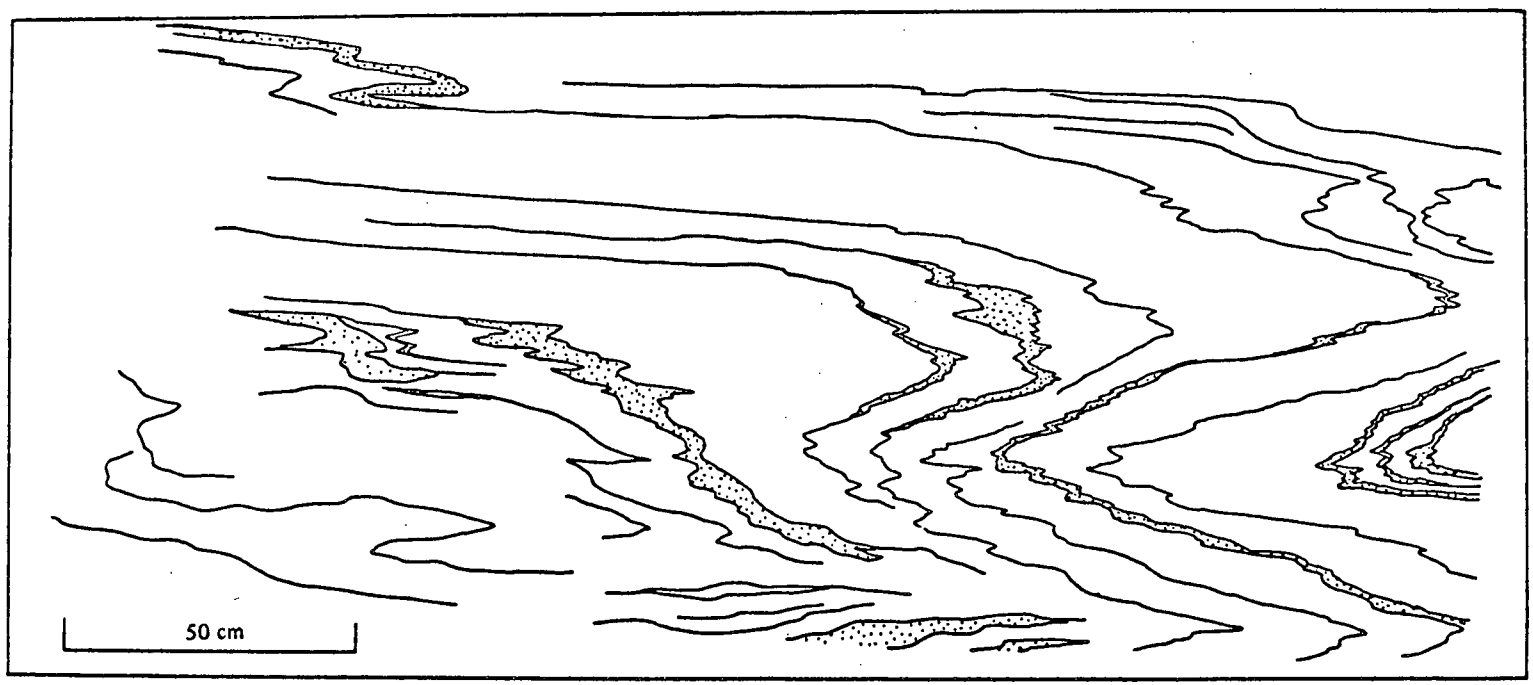


Figure 17. Asymmetrical Style 1 Fold.

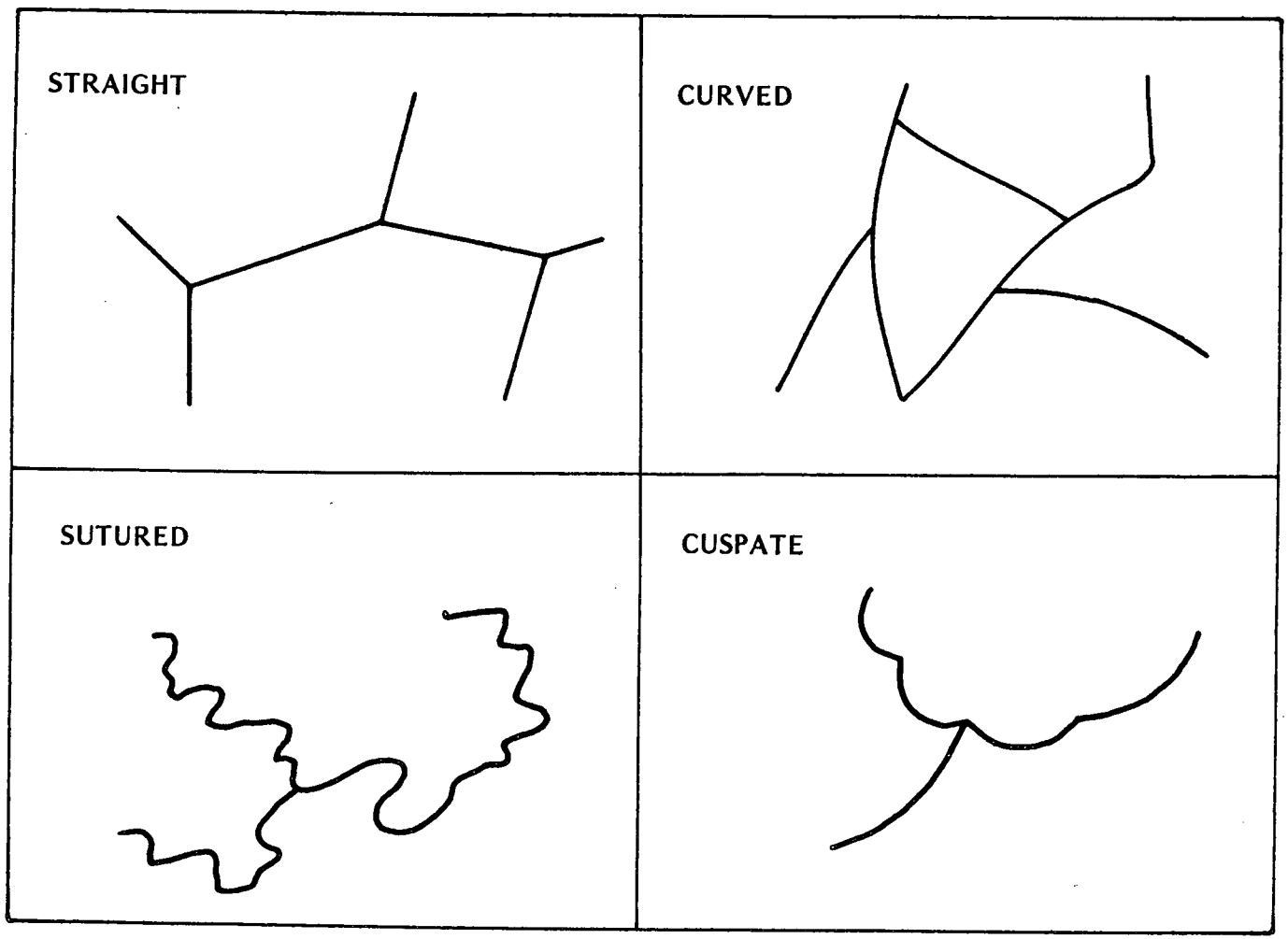


Figure 18. Grain boundary shapes.

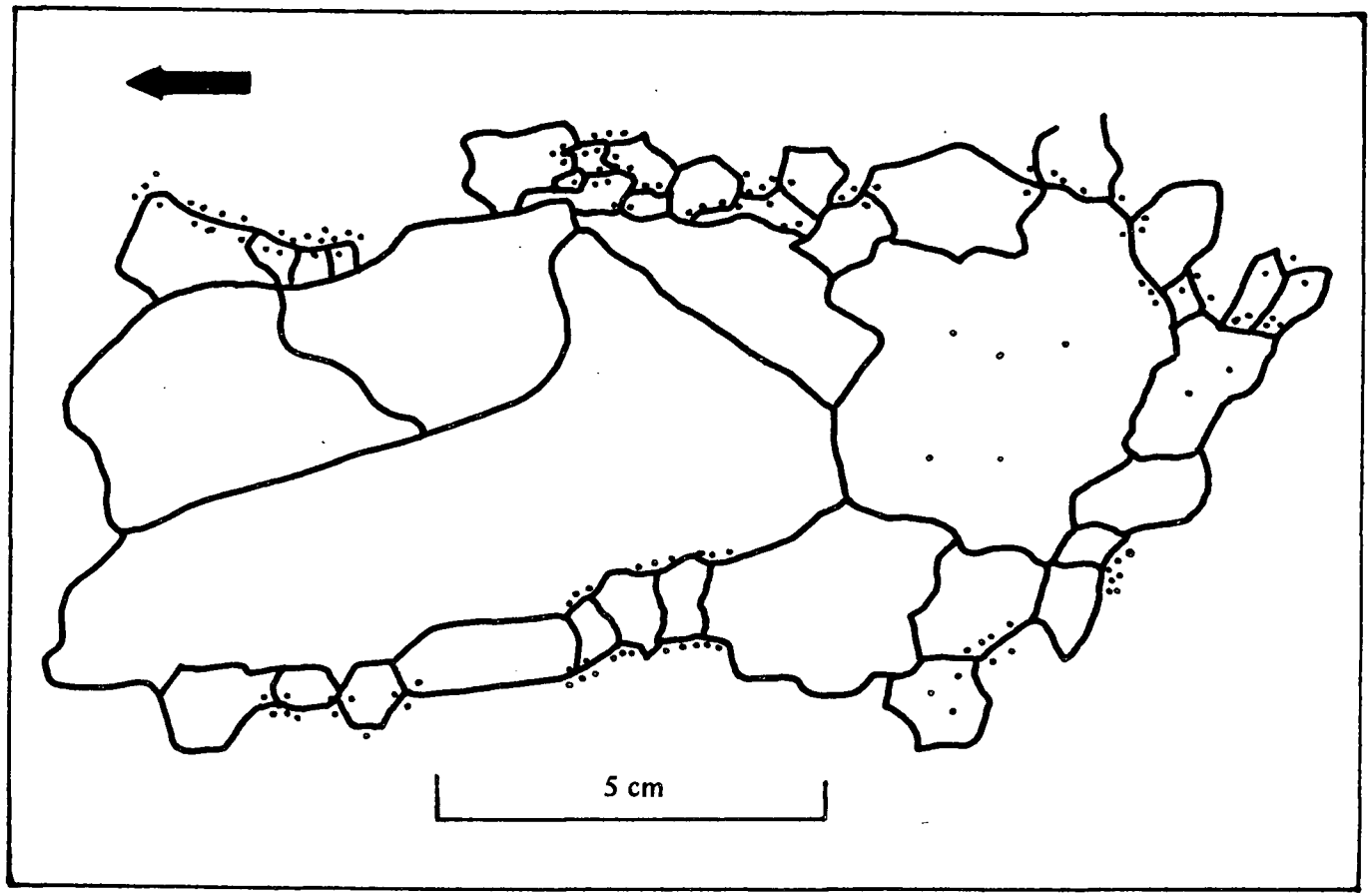


Figure 19. Grain boundary shapes on cellar wall. Redrawn from pencil rubbing. Arrow shows approximate flow direction.

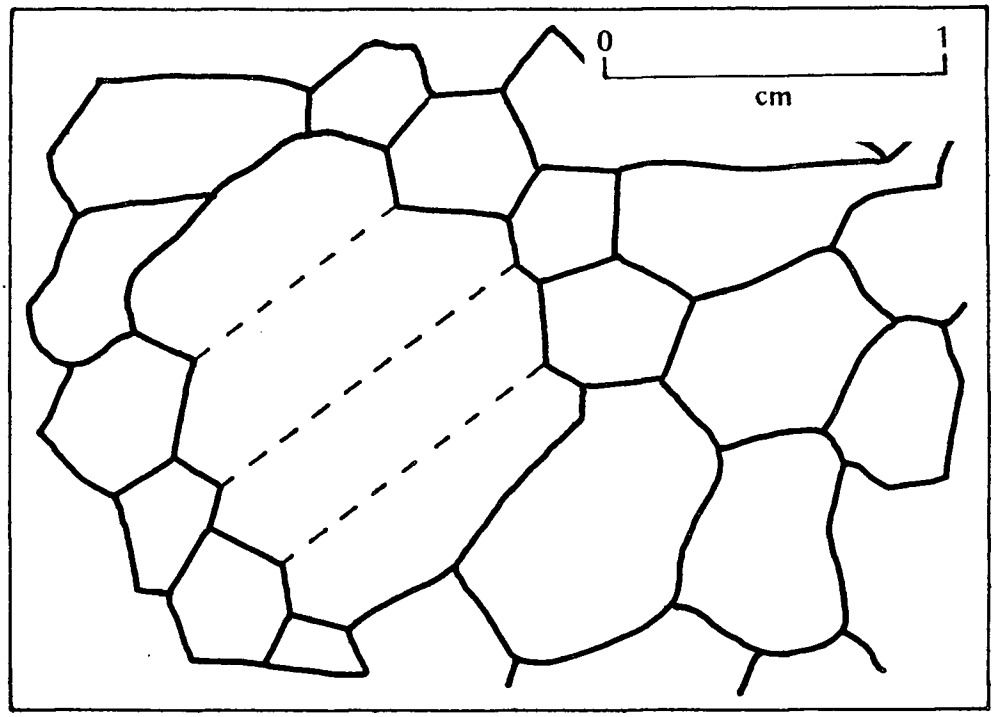


Figure 20. Relict crystal shows deformation bands. Note tendency to 120° angles at boundary triple points.

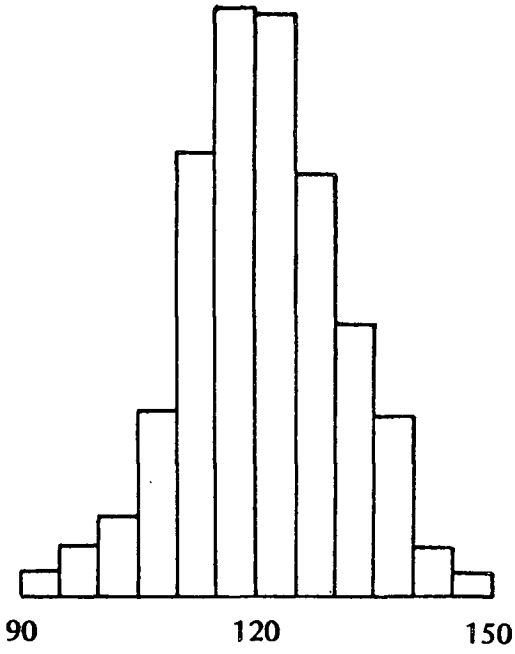


Figure 21. Frequency distribution of boundary angles of small strain-free crystals surrounding strained relict crystals.

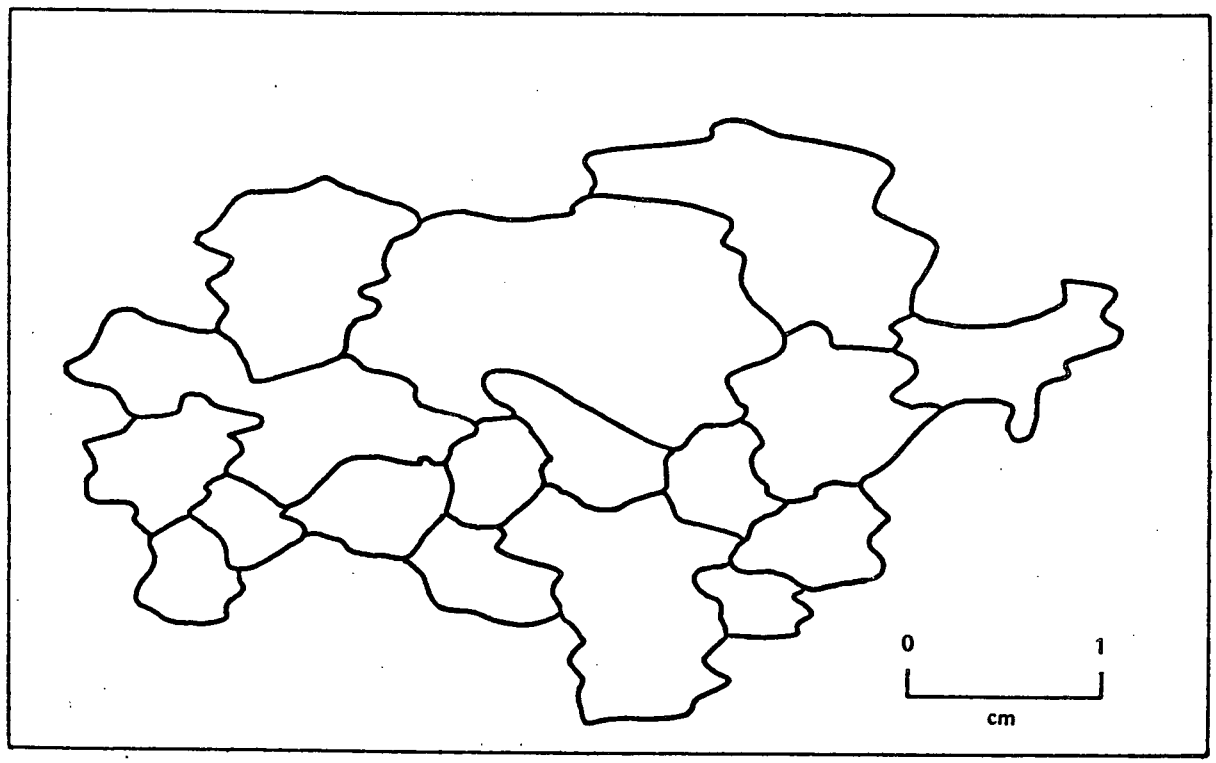


Figure 22. Texture-type IIa. Serrated boundaries.

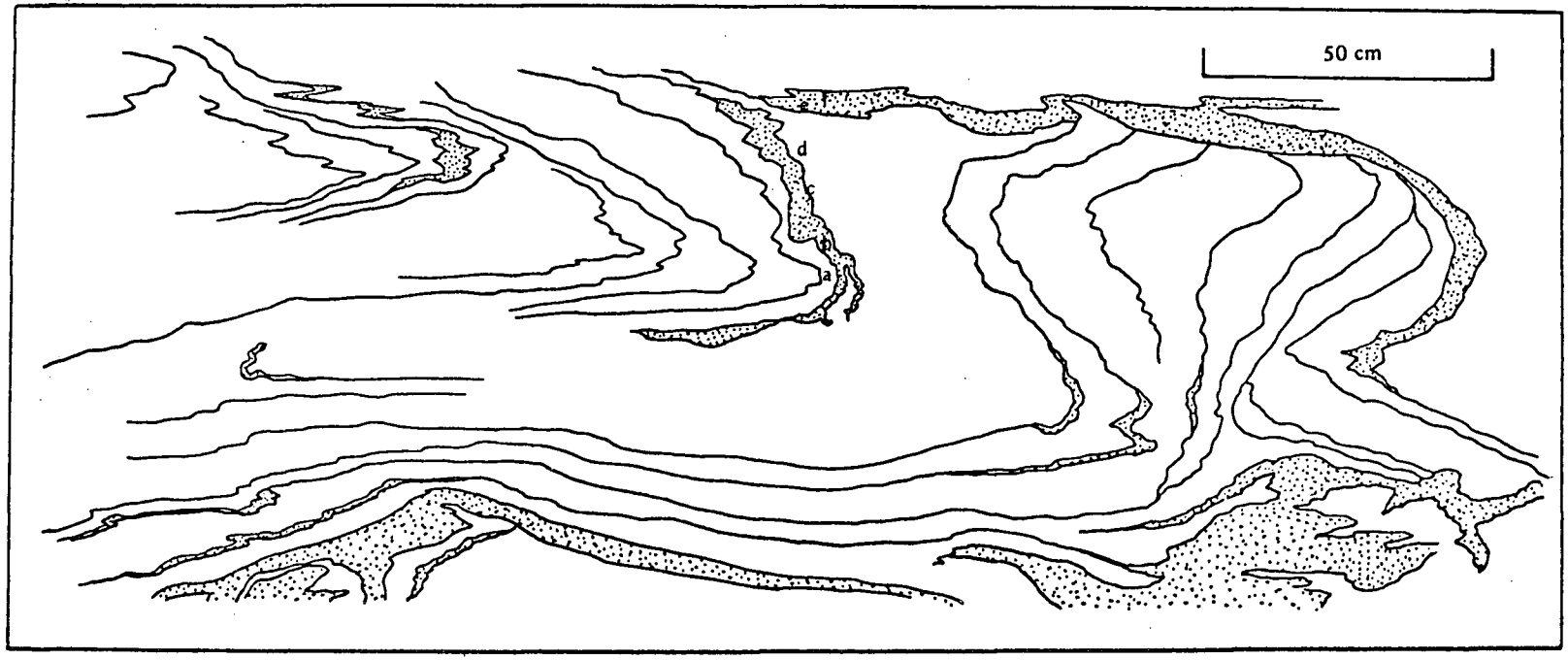


Figure 23. Positions of samples for sediment content, First Style 1 Fold.

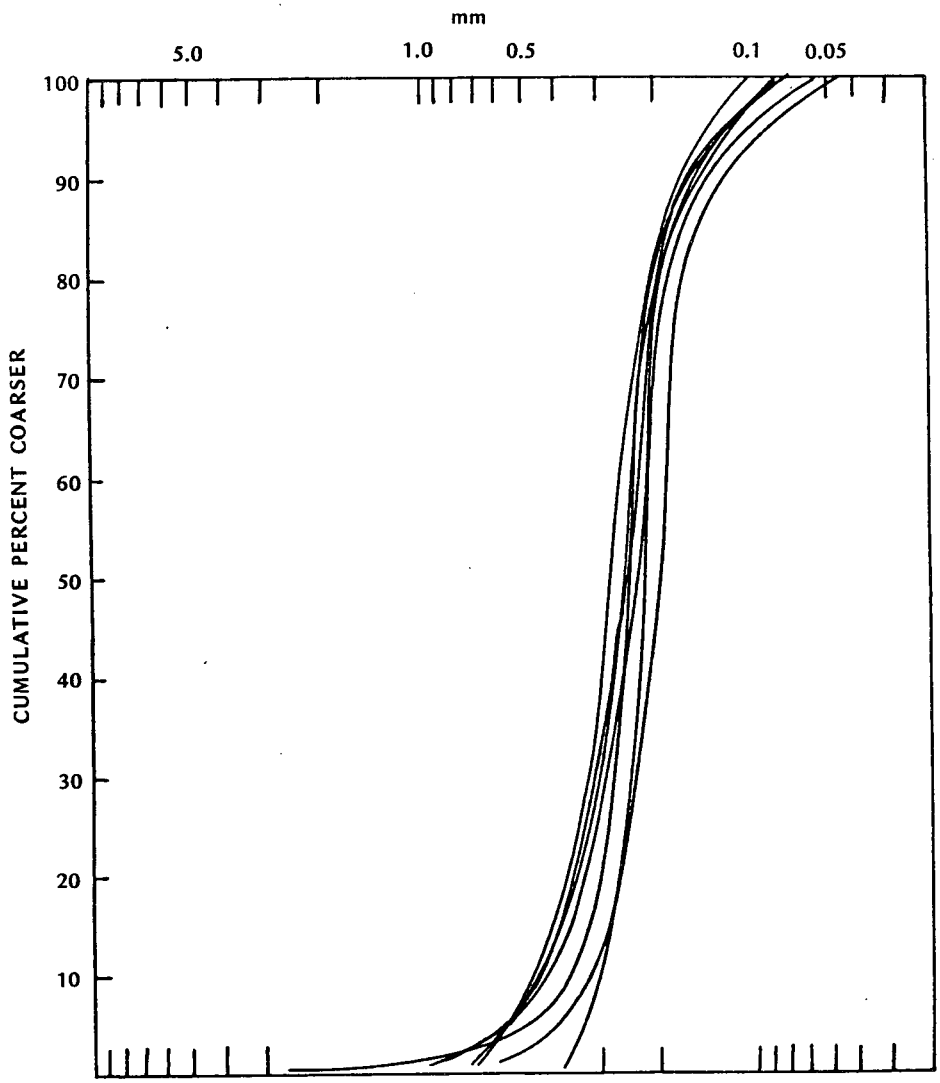


Figure 24. Sediment-size curves

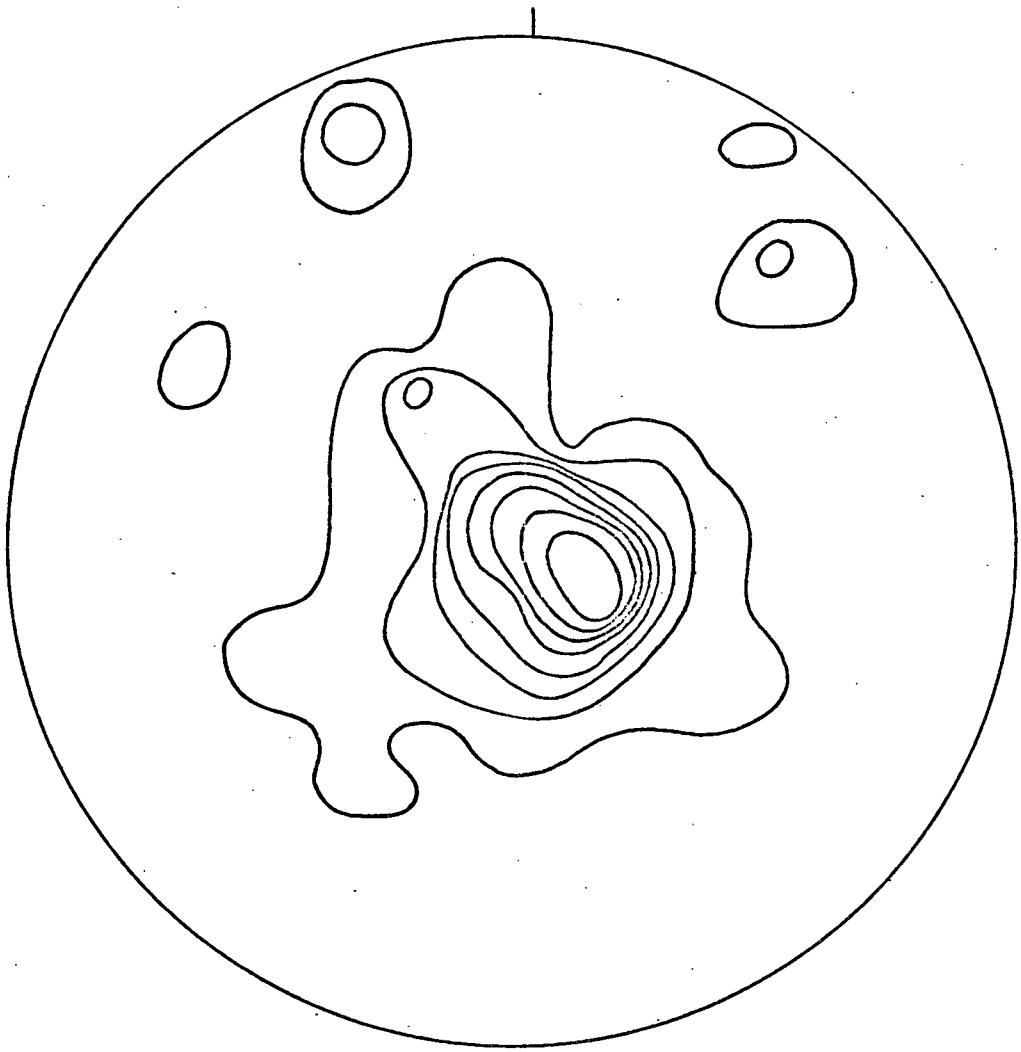


DIAGRAM 1 HORIZONTAL MAX. 19% 100 CRYSTALS

DIAGRAM 2 VERTICAL MAX. 16% 100 CRYSTALS

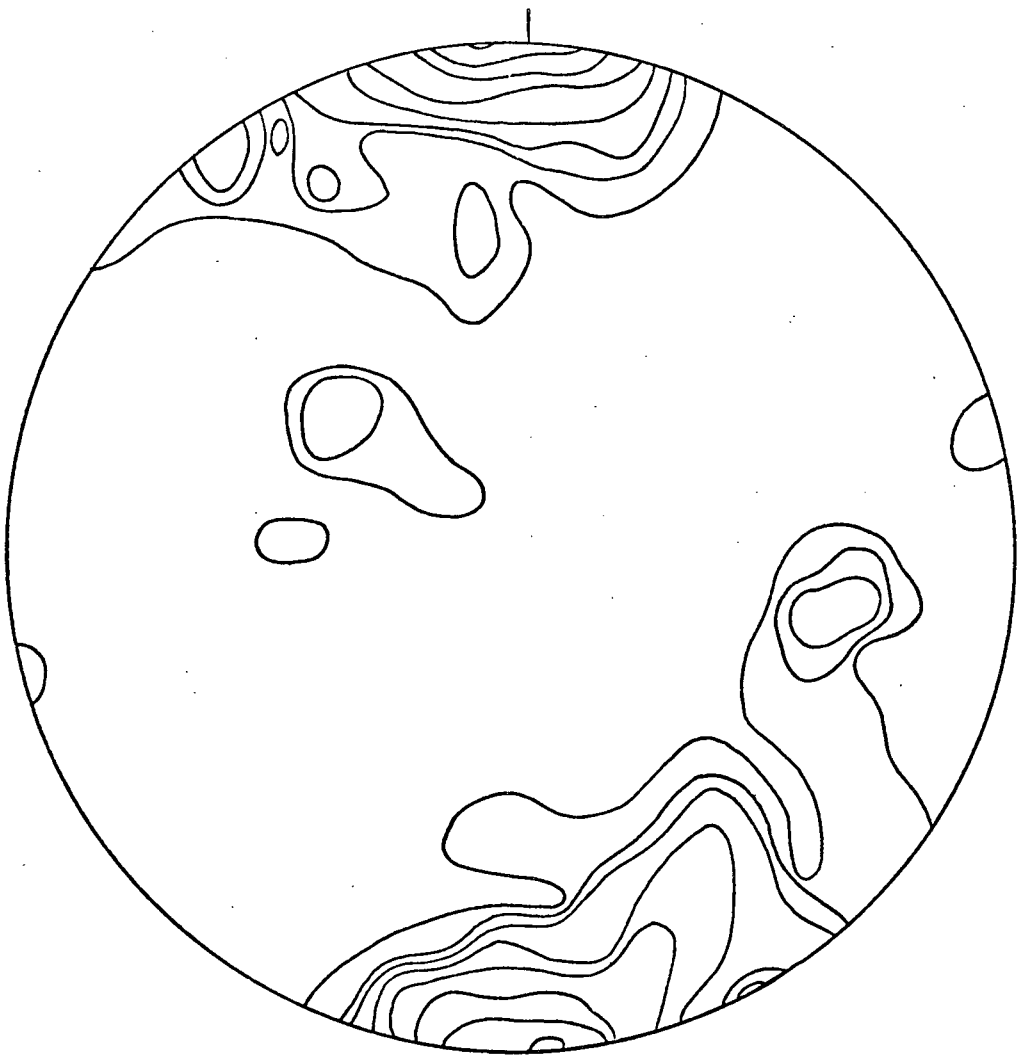


DIAGRAM 3 VERTICAL MAX. 15% 100 CRYSTALS

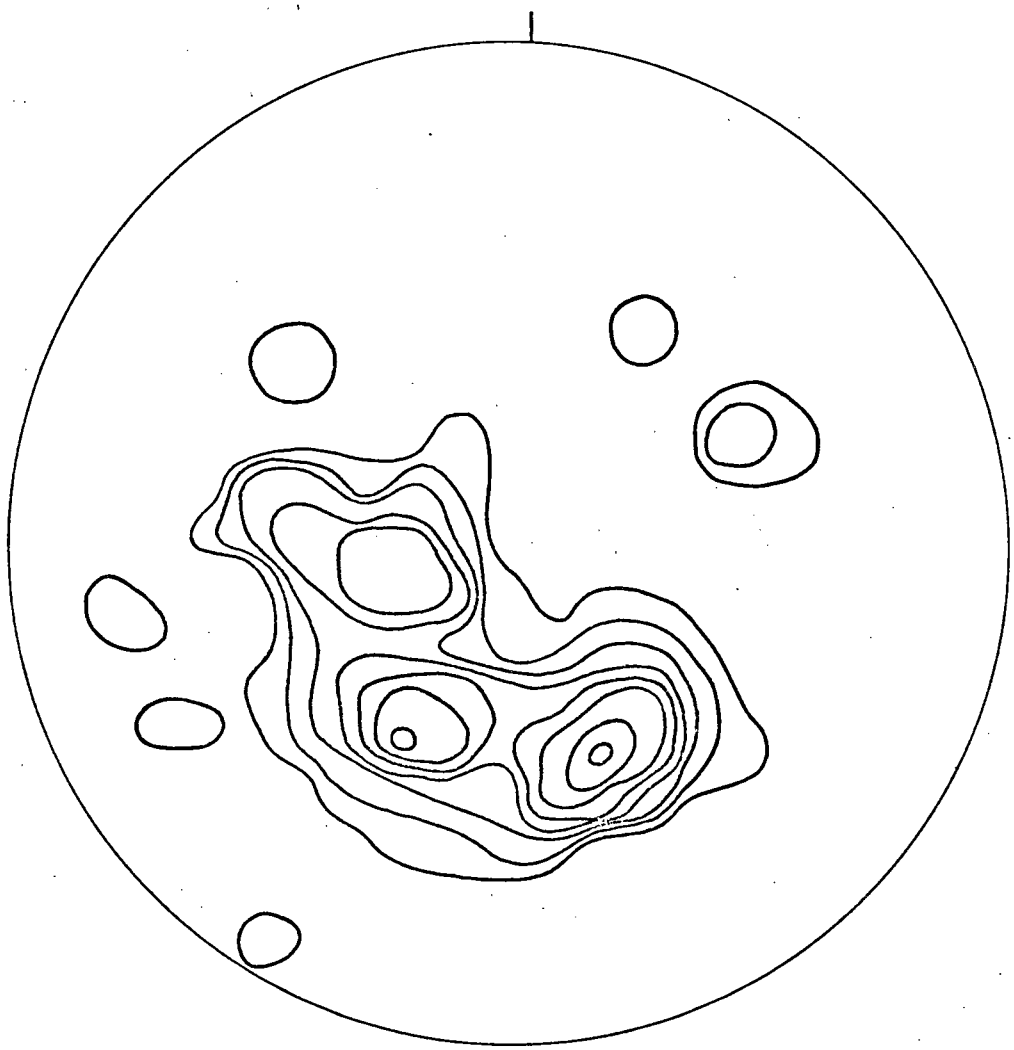


DIAGRAM 4 HORIZONTAL MAX. 16% 100 CRYSTALS

DIAGRAM 5 HORIZONTAL MAX. 19% 150 CRYSTALS

DIAGRAM 6 VERTICAL MAX. 12% 175 CRYSTALS

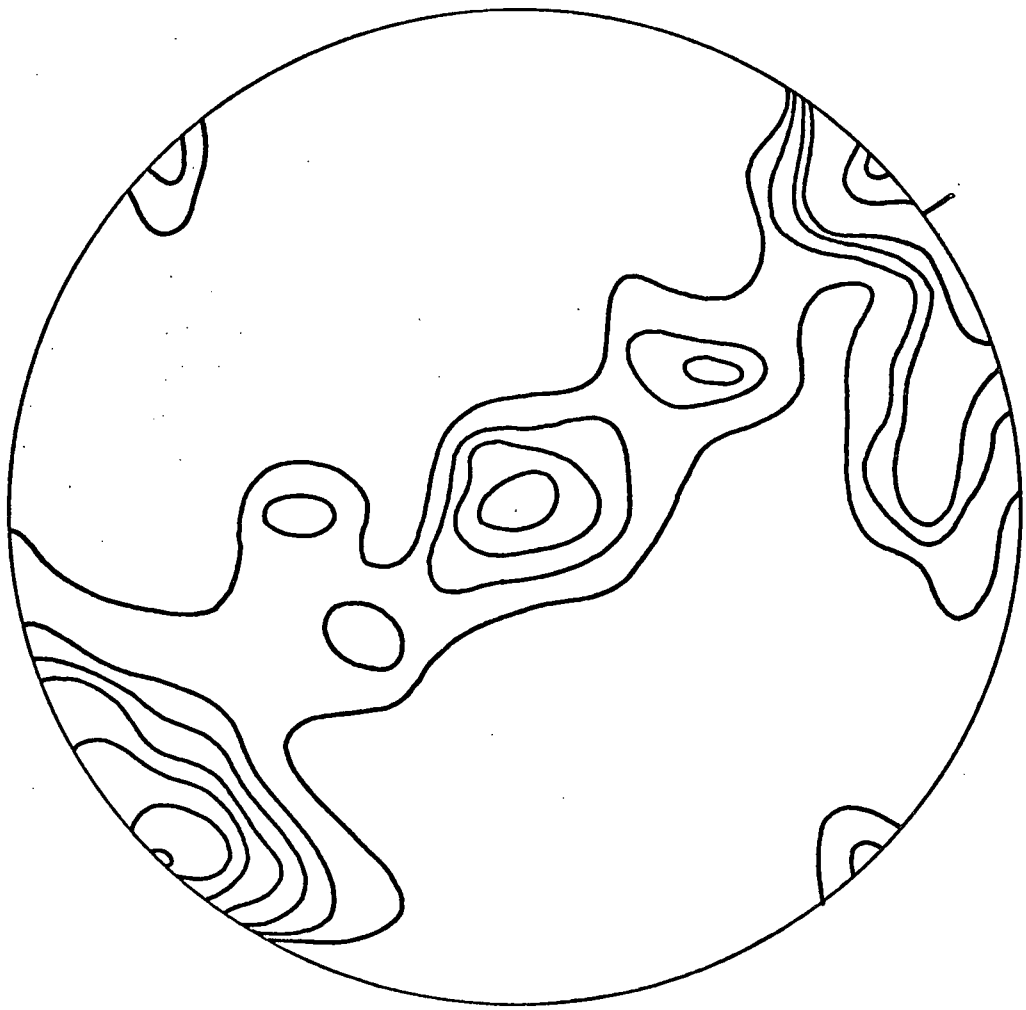


DIAGRAM 7 VERTICAL MAX. 13% 100 CRYSTALS

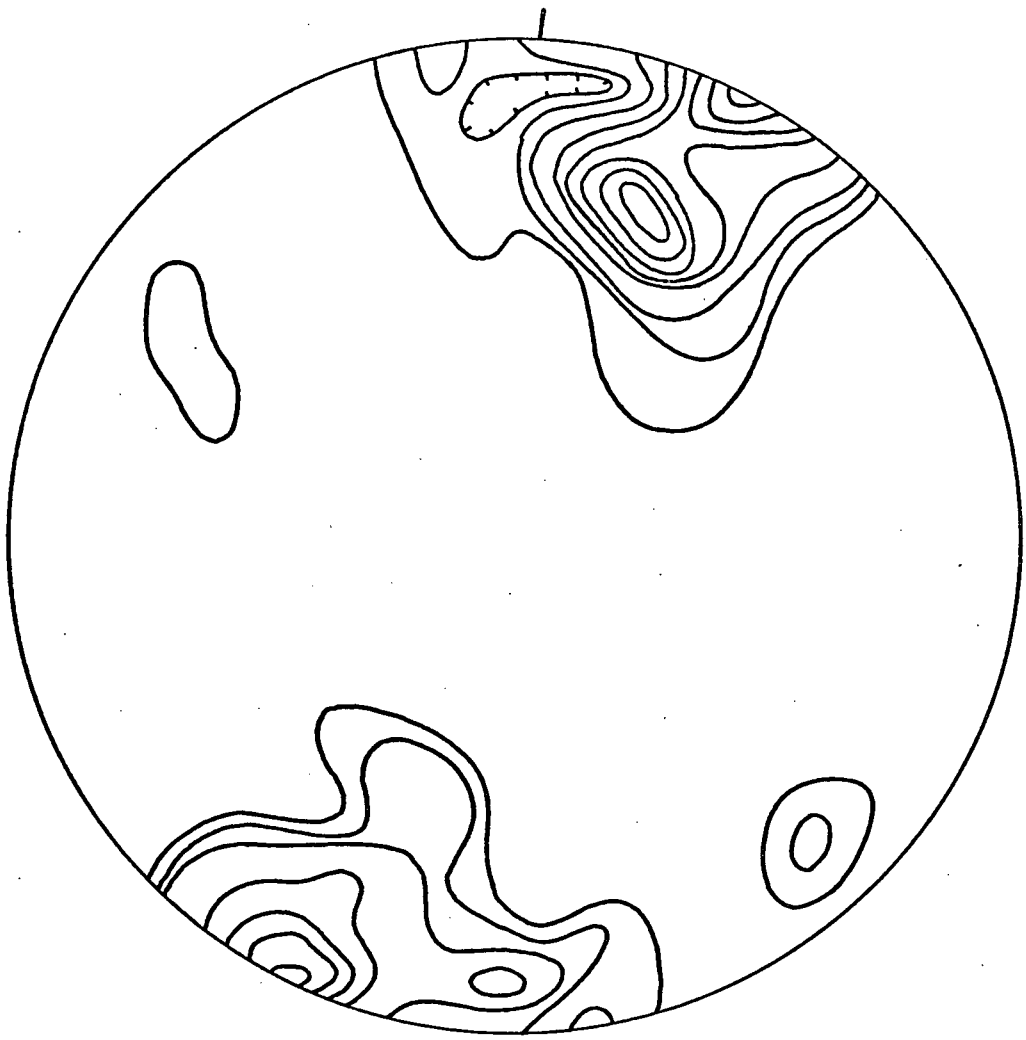


DIAGRAM 8 VERTICAL MAX. 17% 100 CRYSTALS

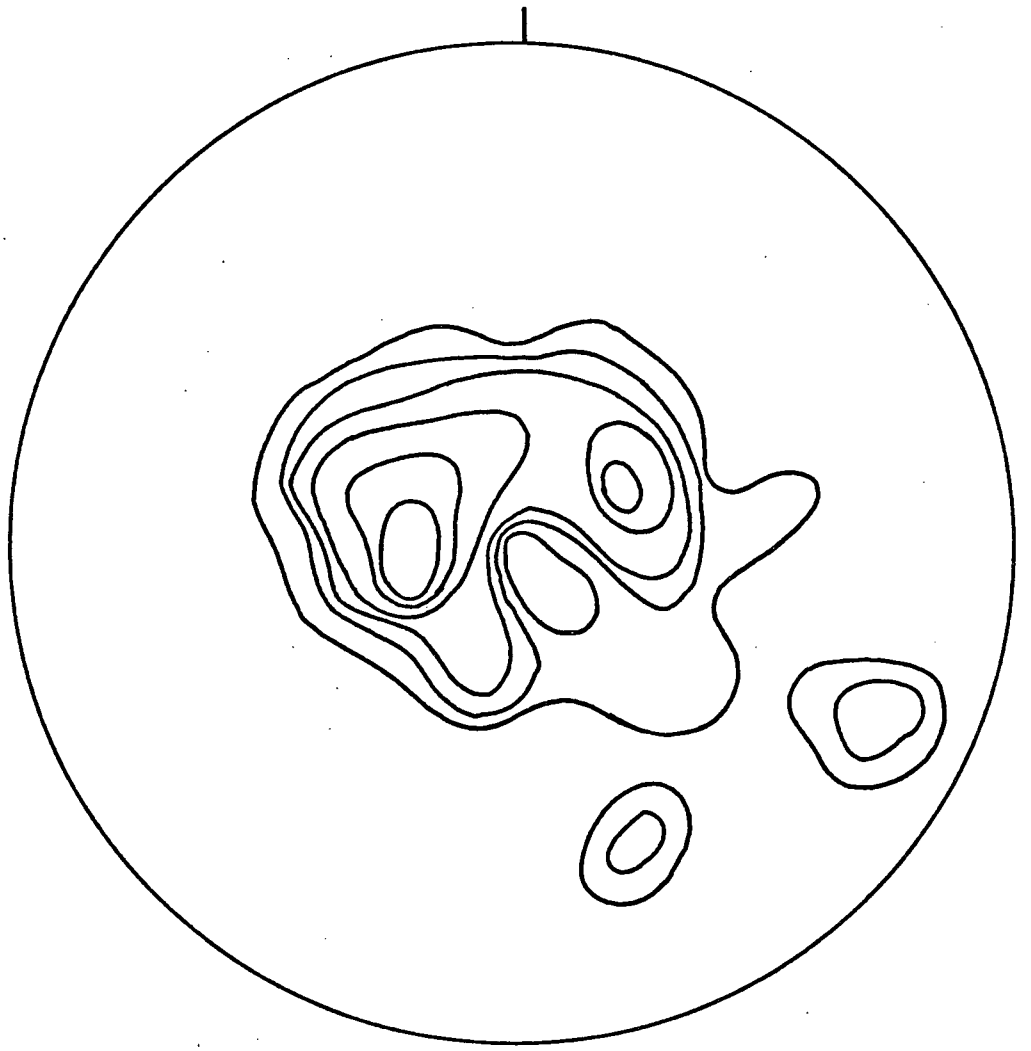


DIAGRAM 9 HORIZONTAL MAX. 11% 75 SMALL CRYSTALS

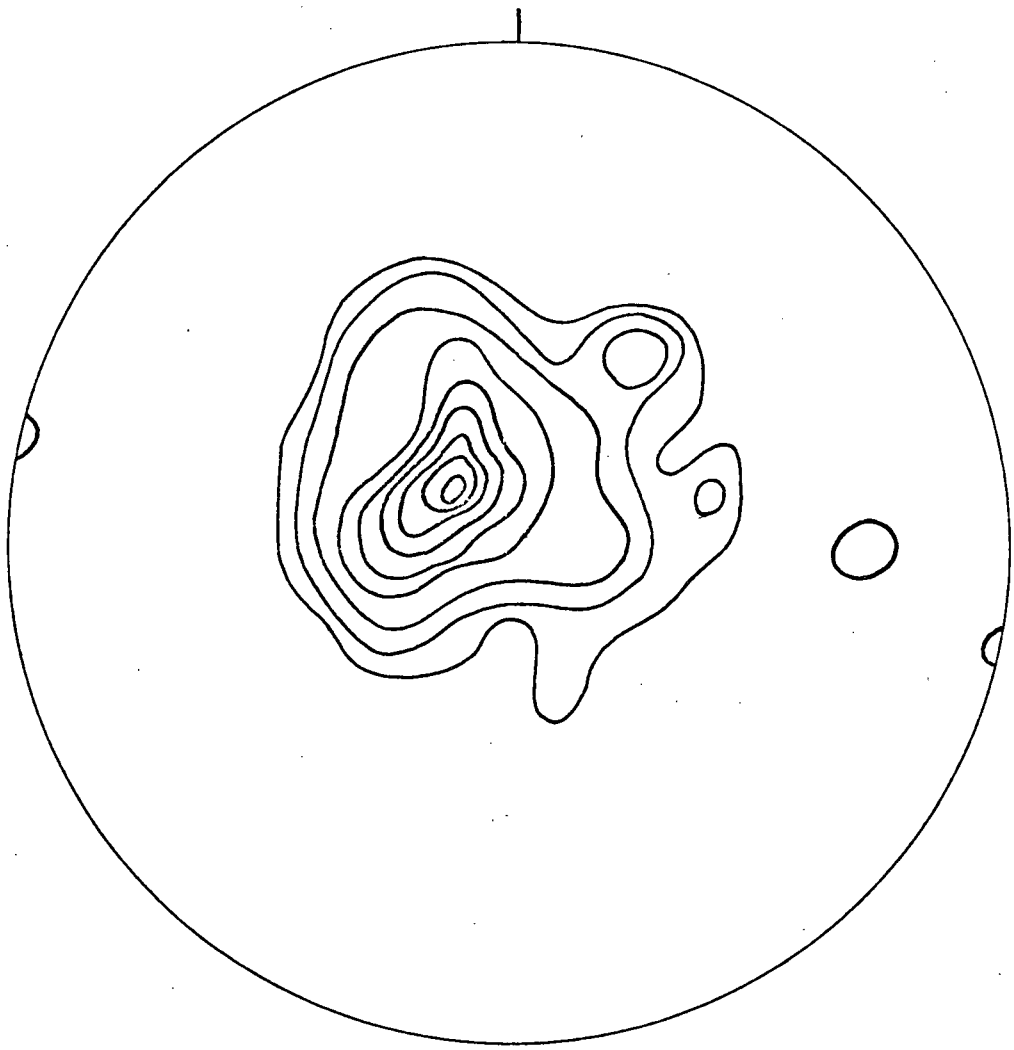


DIAGRAM 10 HORIZONTAL MAX. 18% 200 LARGE CRYSTALS

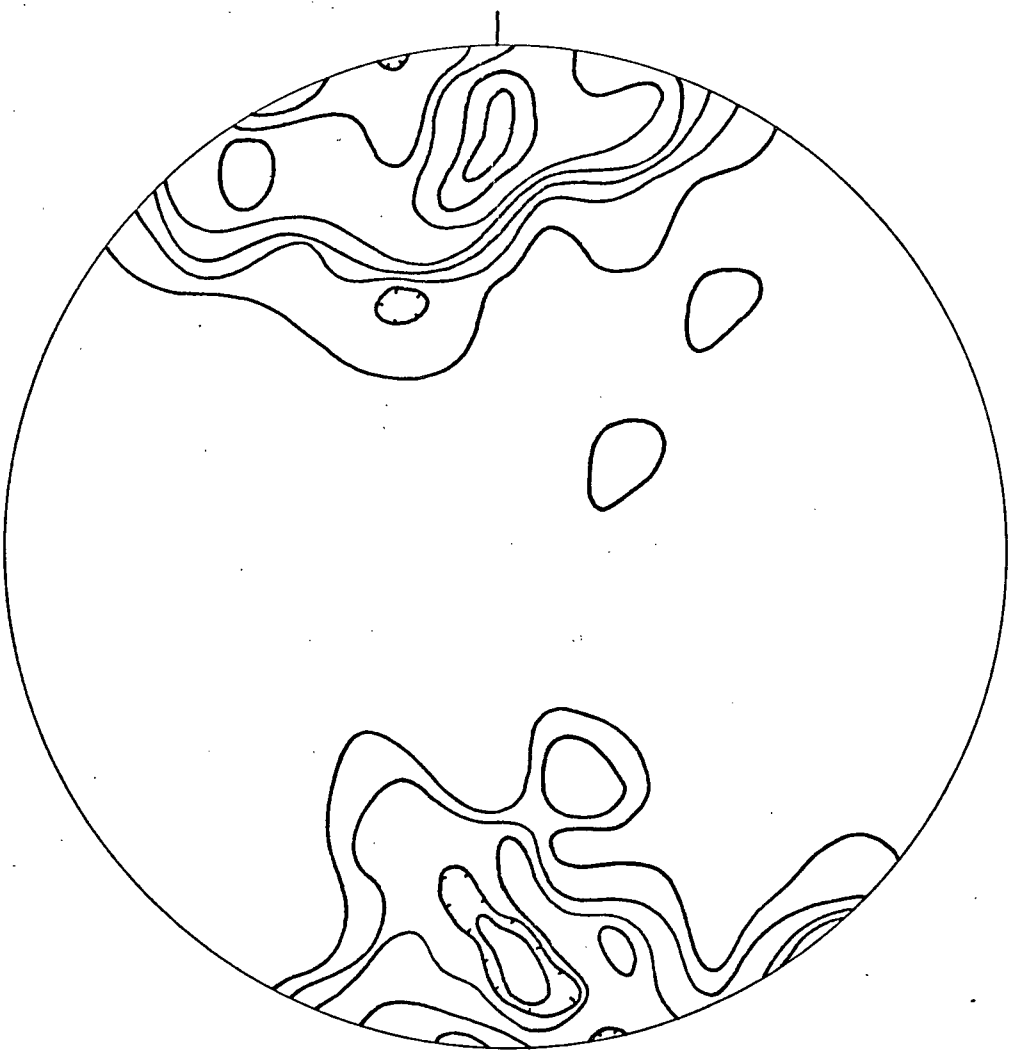


DIAGRAM 11 VERTICAL MAX. 13% 100 CRYSTALS

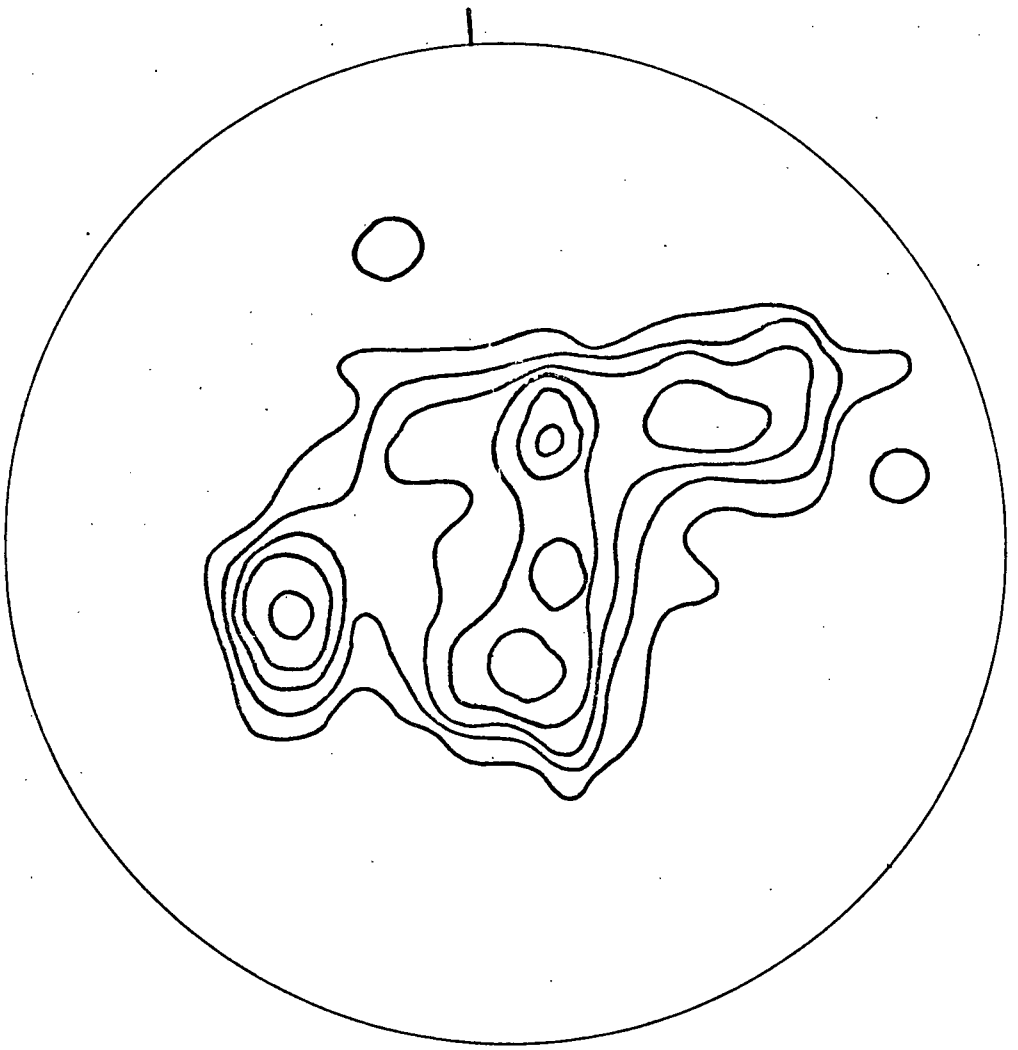


DIAGRAM 12 HORIZONTAL MAX. 11% 250 CRYSTALS

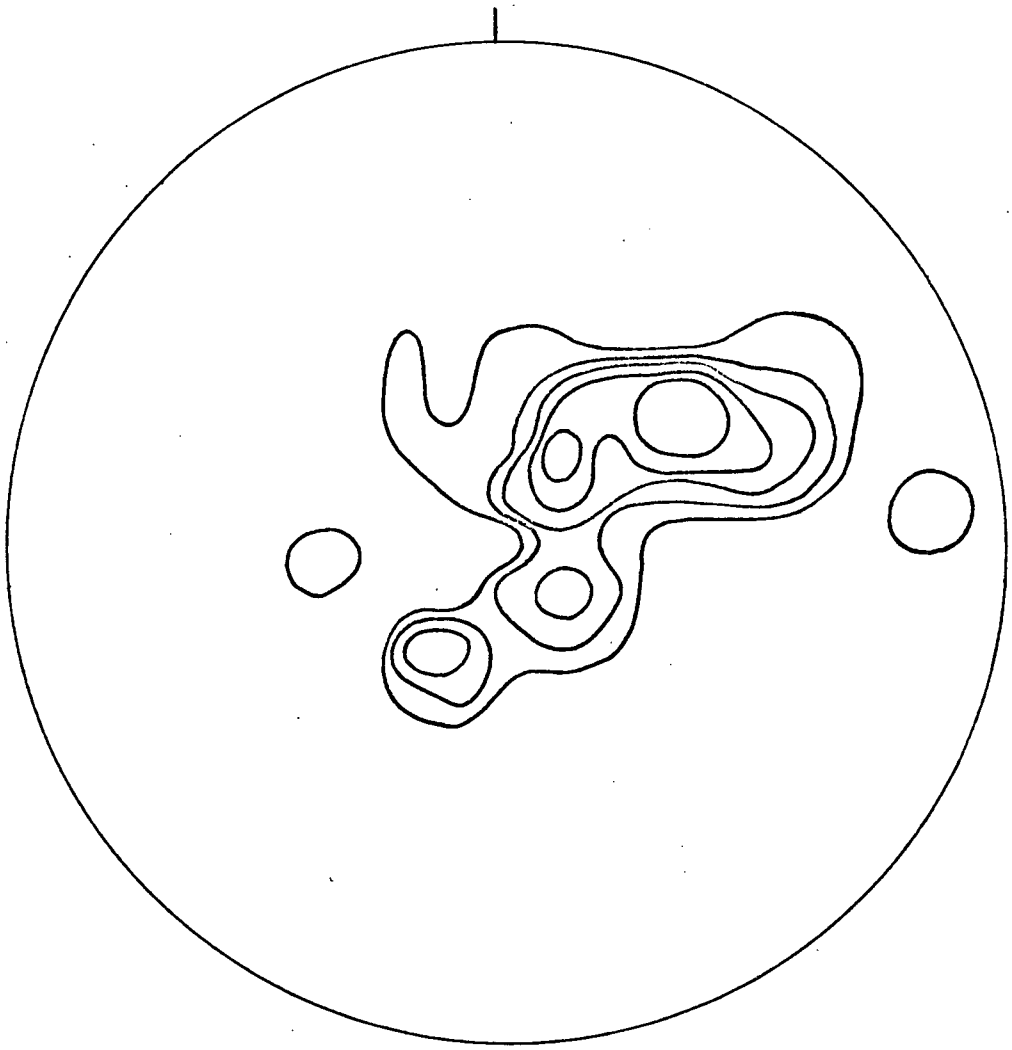


DIAGRAM 13 HORIZONTAL MAX. 8% 50 CRYSTALS

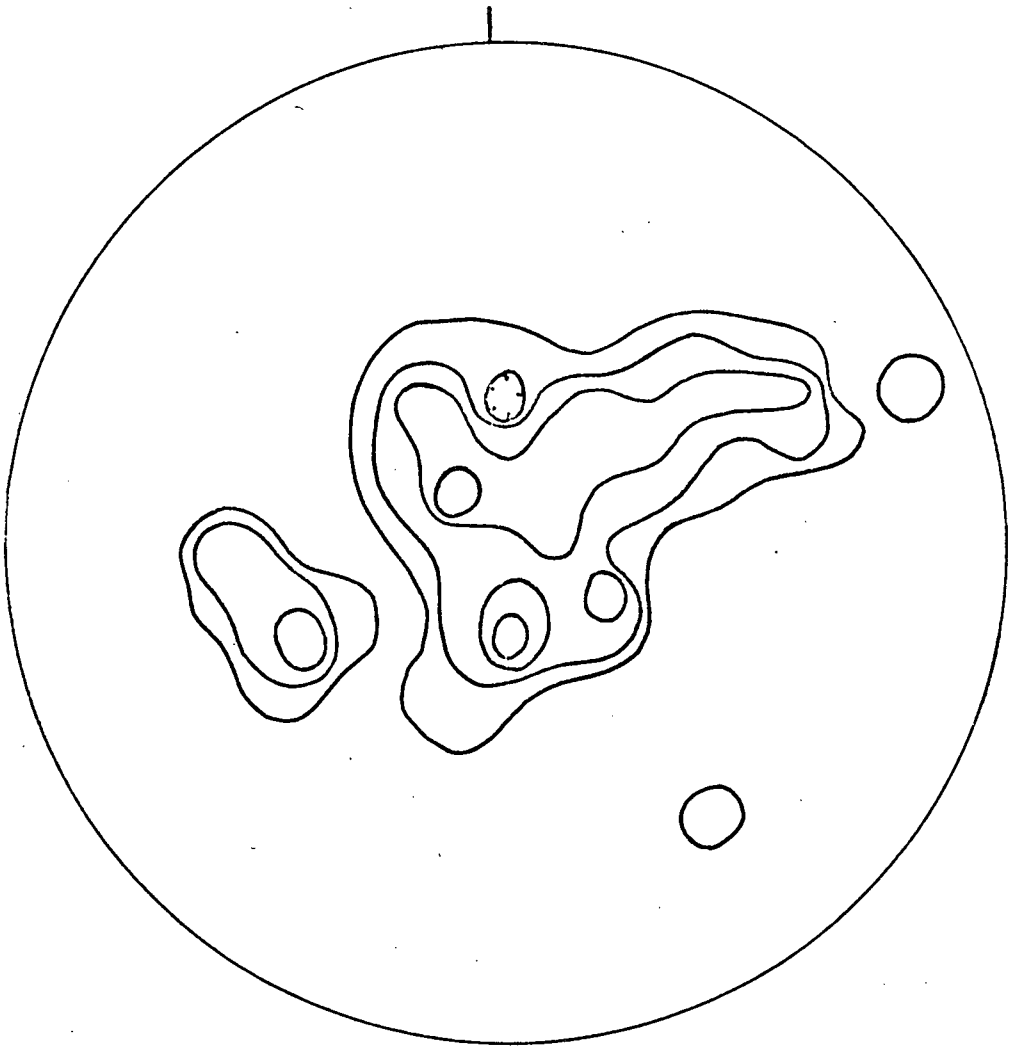


DIAGRAM 14 HORIZONTAL MAX. 6% 50 CRYSTALS

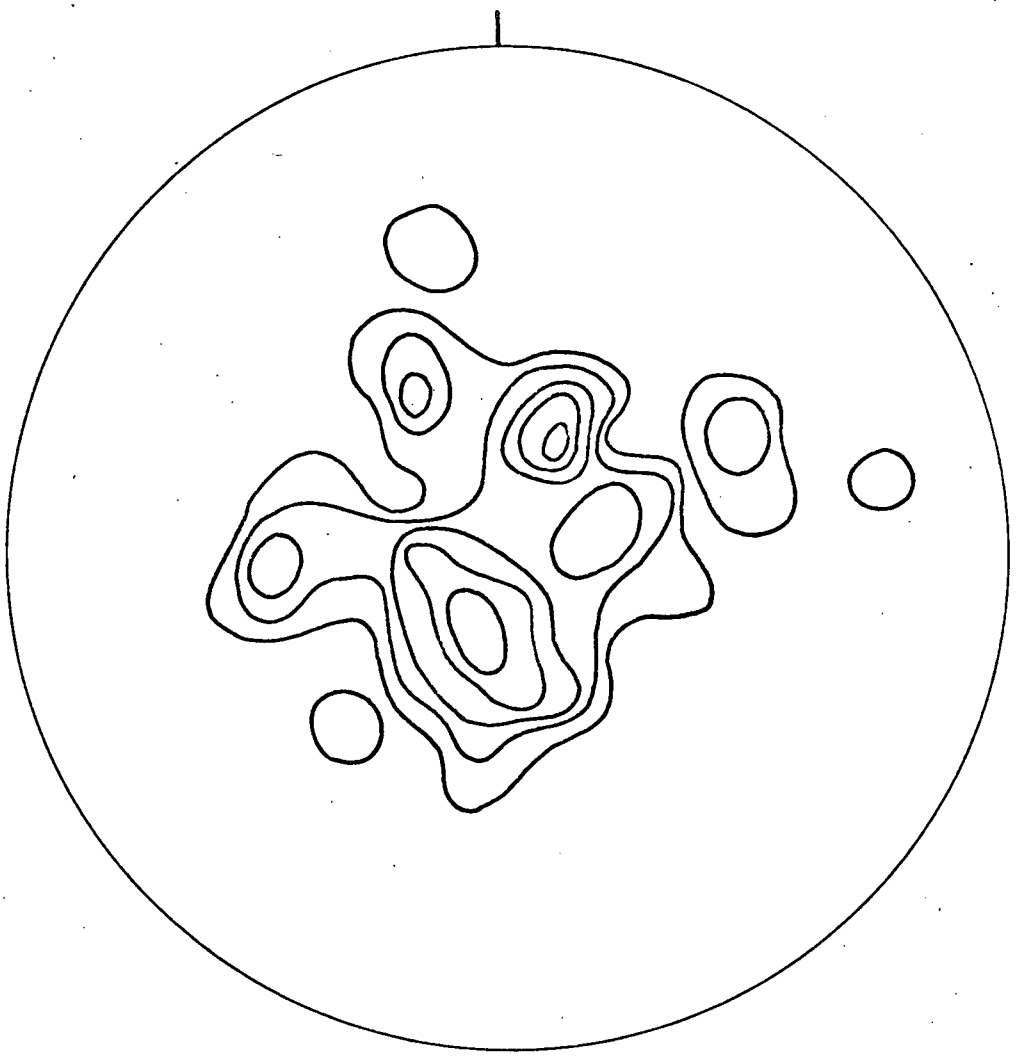


DIAGRAM 15 HORIZONTAL MAX. 8% 50 CRYSTALS

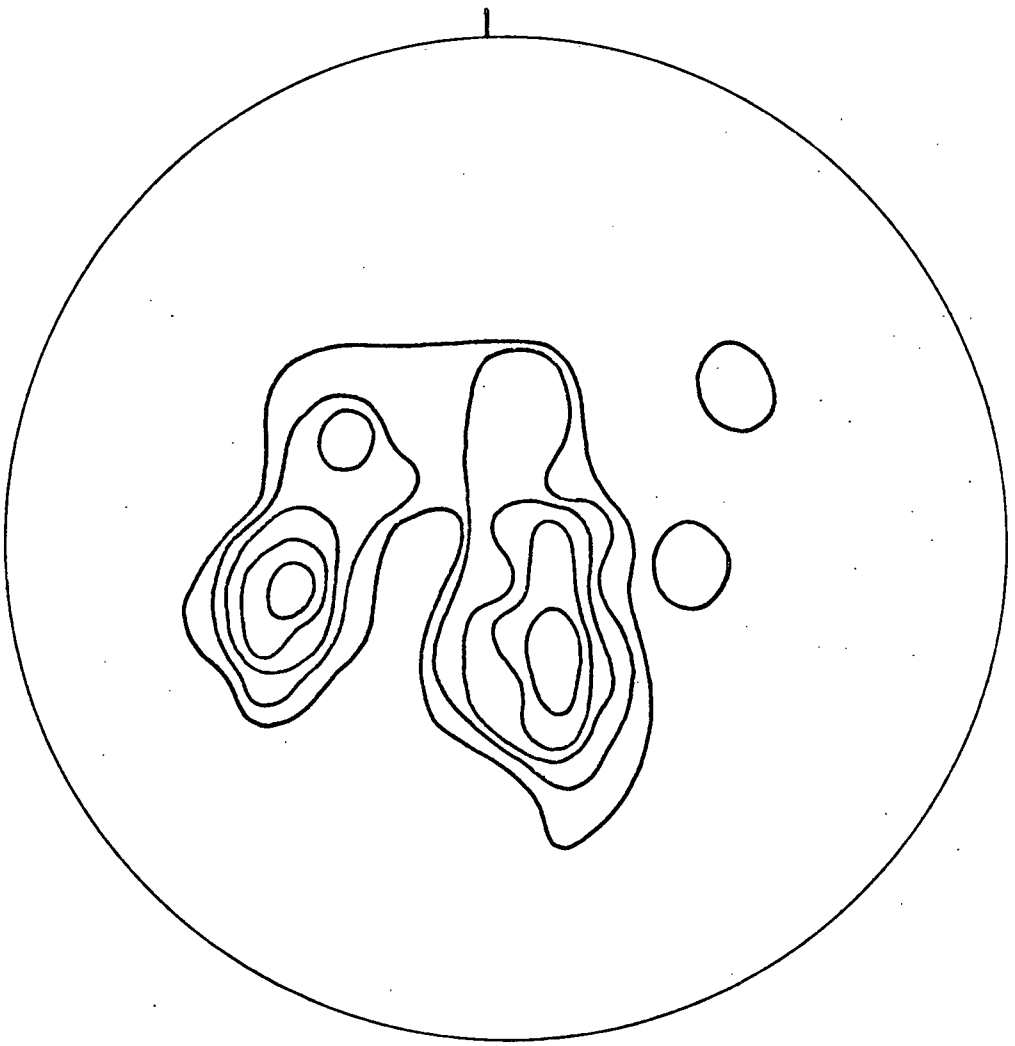


DIAGRAM 16 HORIZONTAL MAX 9% 100 CRYSTALS

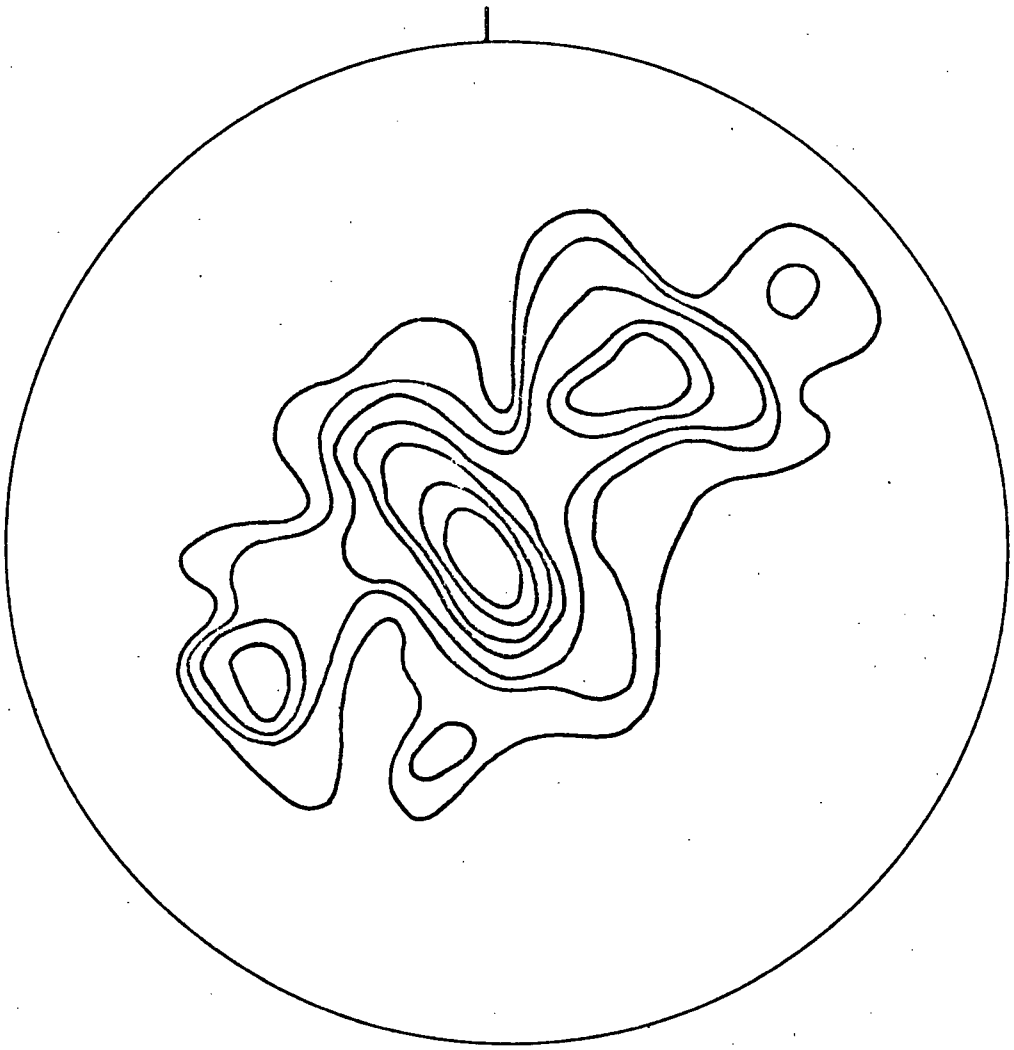


DIAGRAM 17 HORIZONTAL MAX. 13% 100 LARGE CRYSTALS

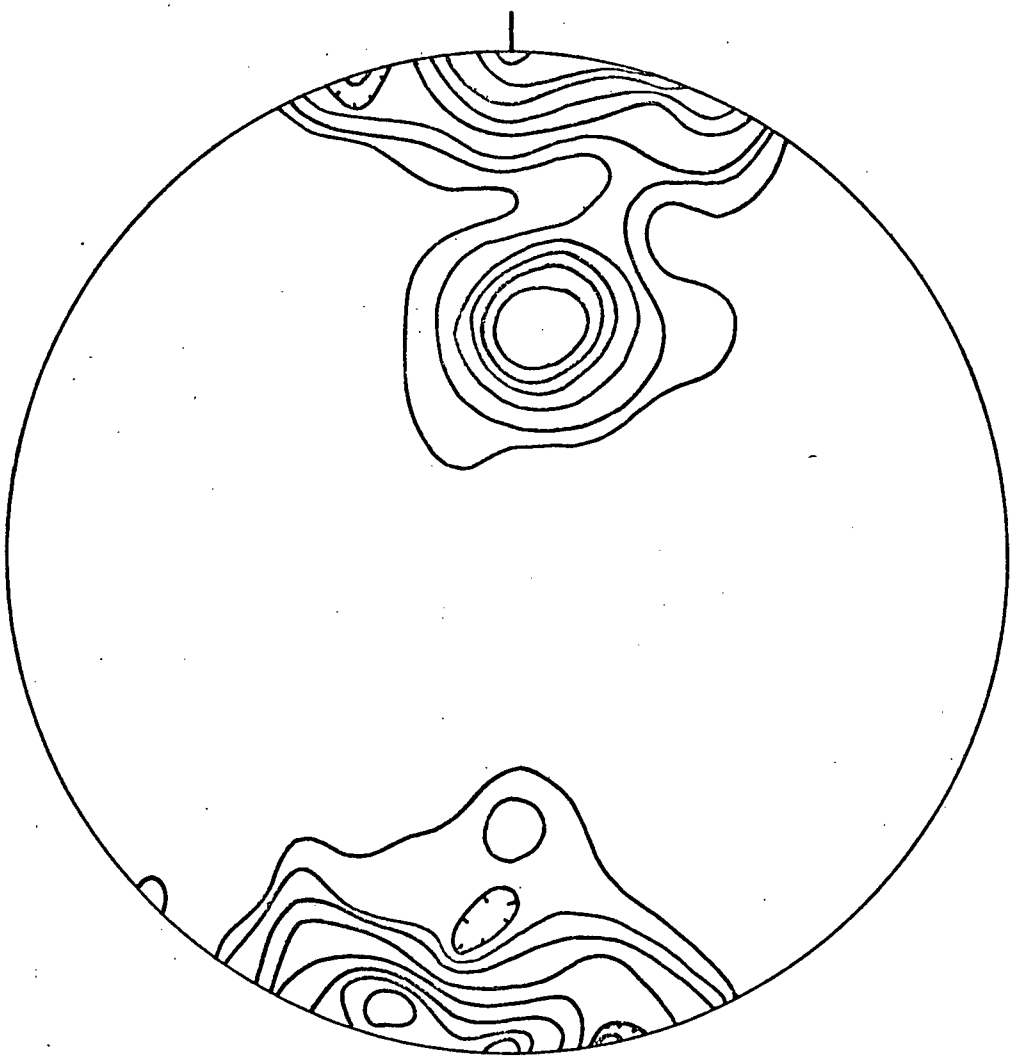


DIAGRAM 18 VERTICAL MAX. 16% 100 CRYSTALS

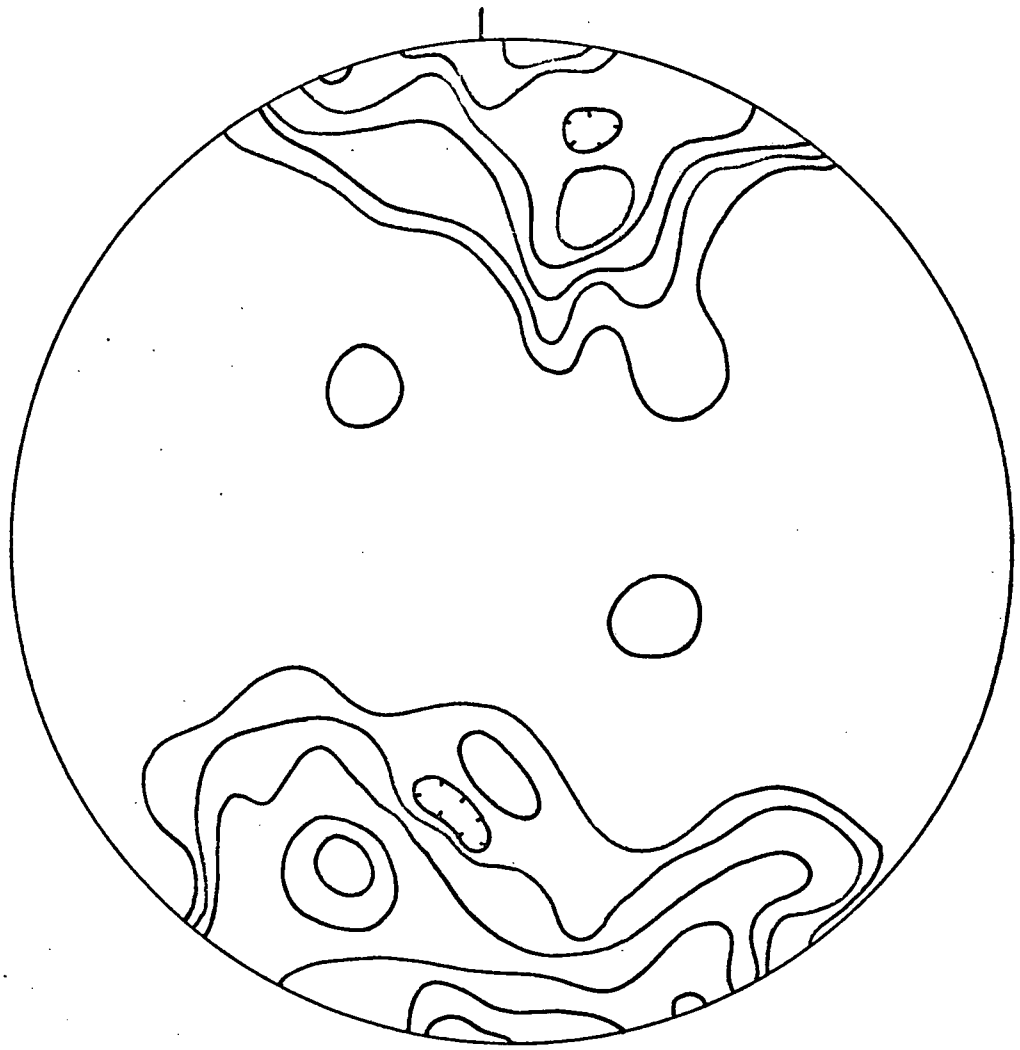


DIAGRAM 19 VERTICAL MAX. 12% 125 CRYSTALS

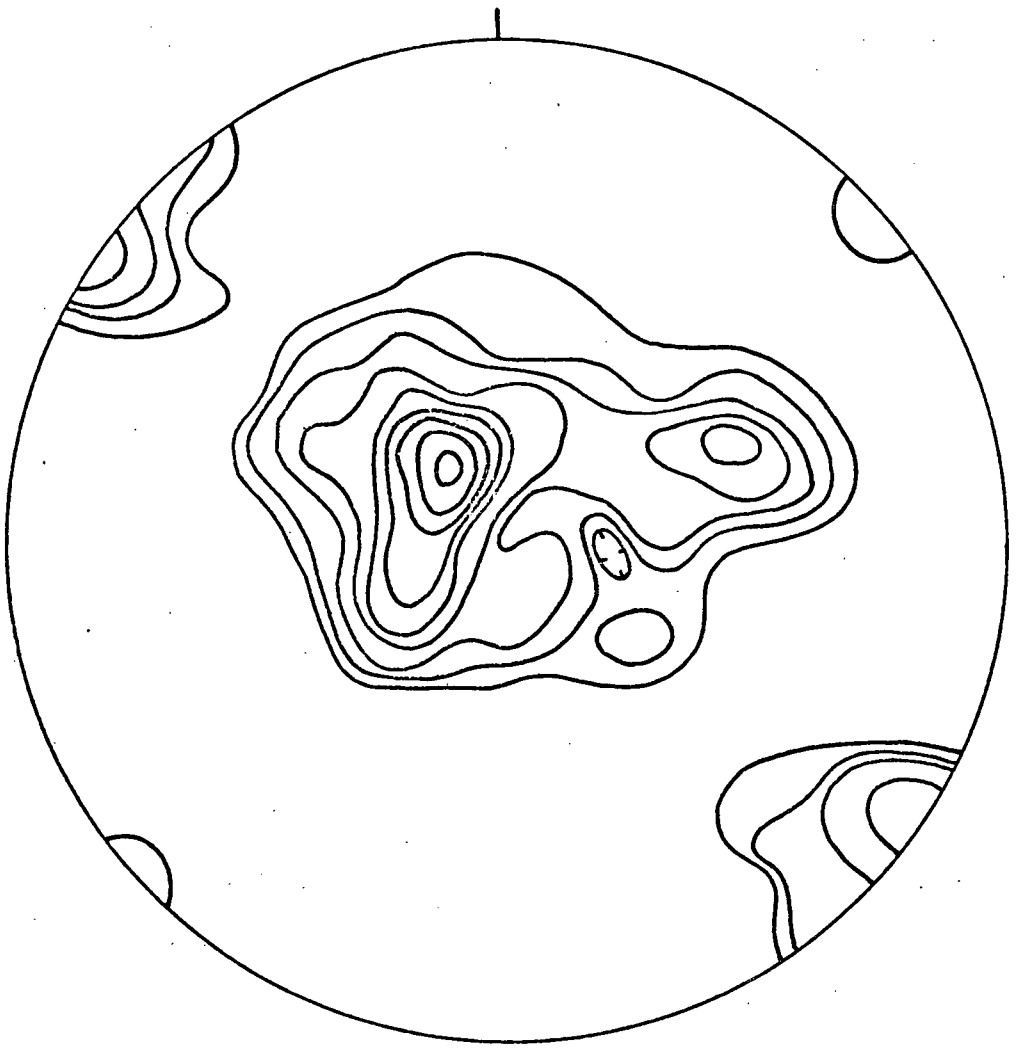


DIAGRAM 20 HORIZONTAL MAX. 18% 200 CRYSTALS

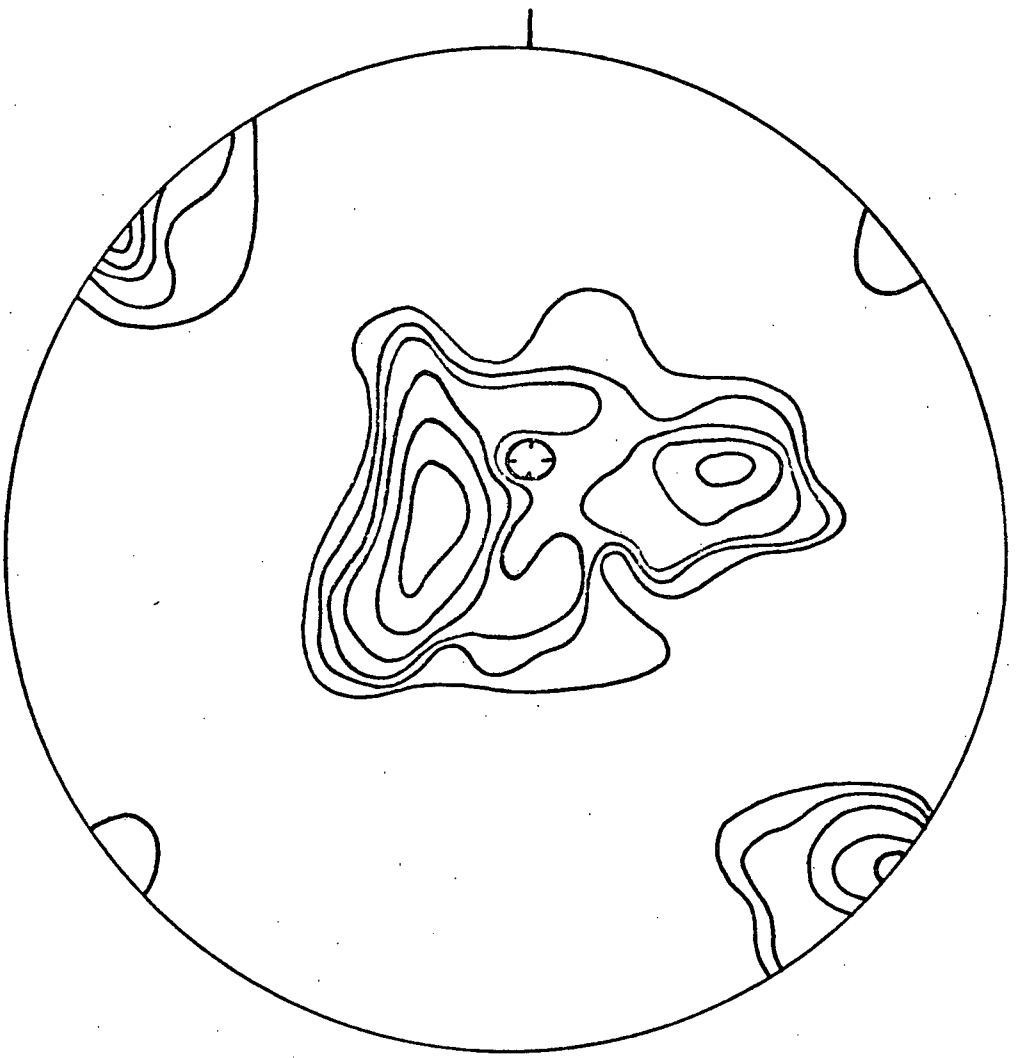


DIAGRAM 21 HORIZONTAL MAX. 11% 110 CRYSTALS

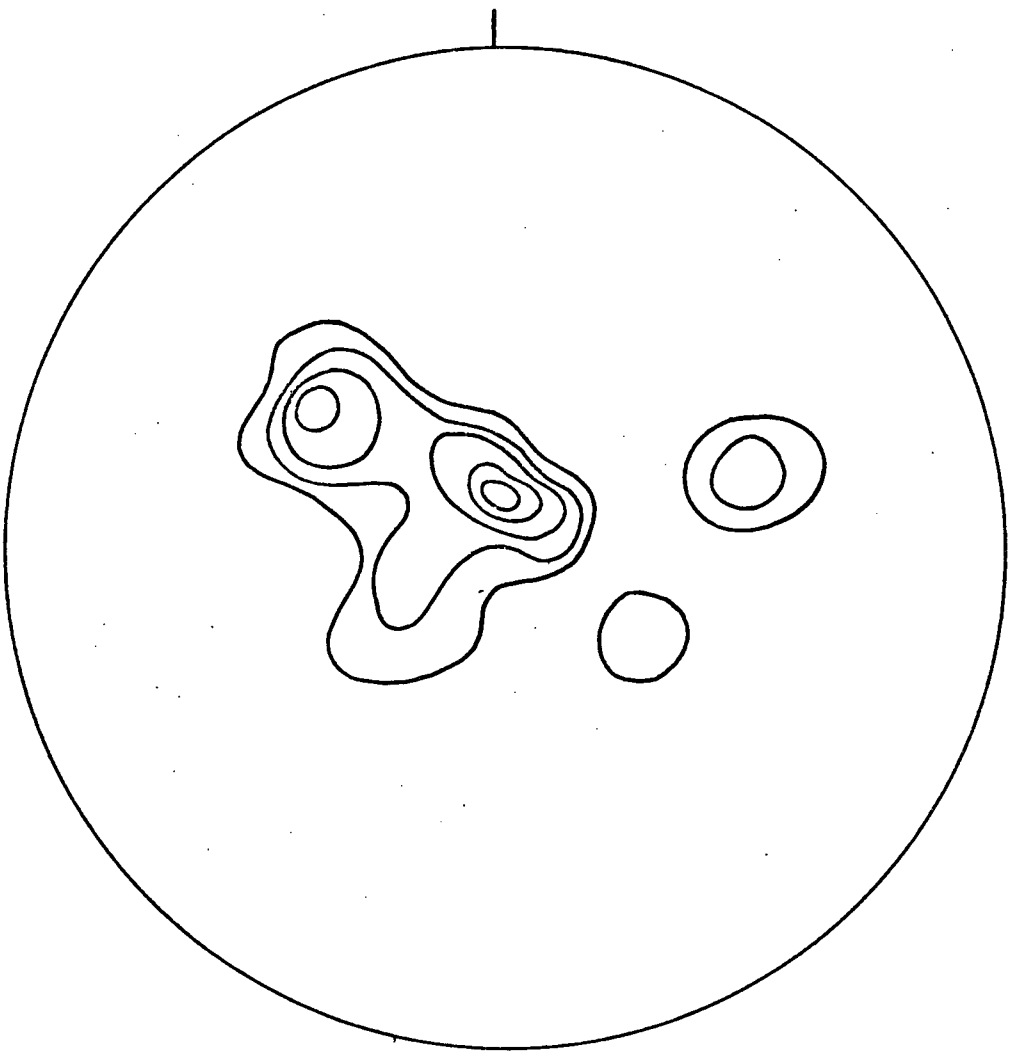


DIAGRAM 22 HORIZONTAL MAX. 8% 47 CRYSTALS

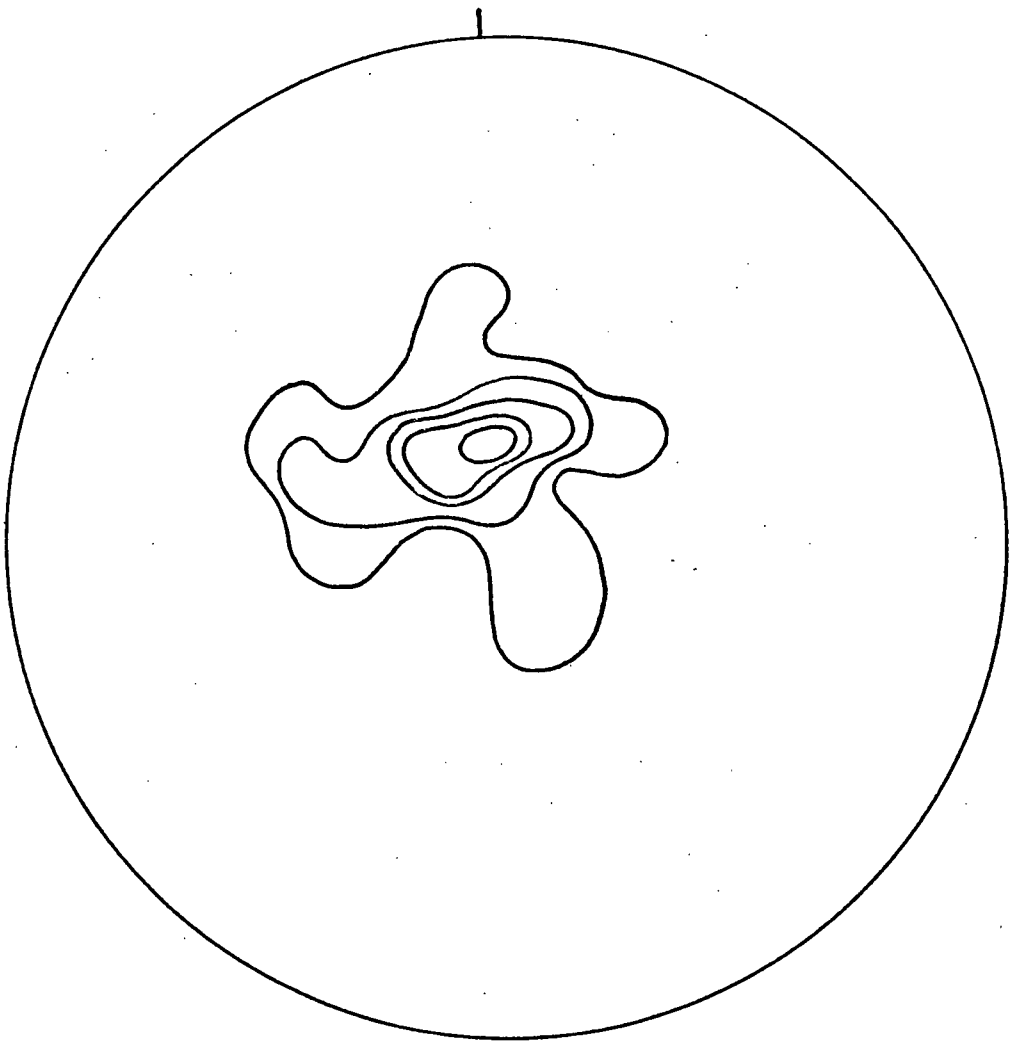


DIAGRAM 23 HORIZONTAL MAX. 8% 43 CRYSTALS

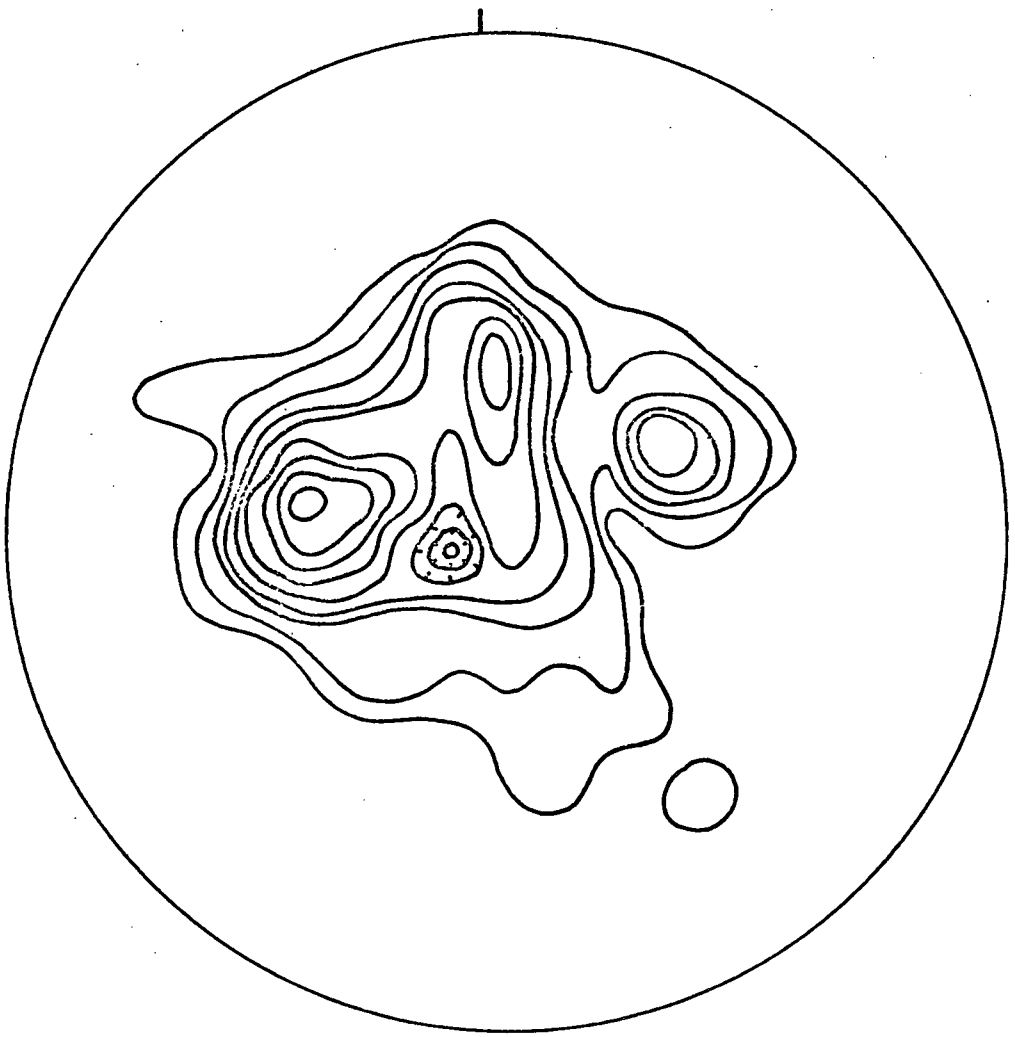


DIAGRAM 24 HORIZONTAL MAX. 18% 175 CRYSTALS

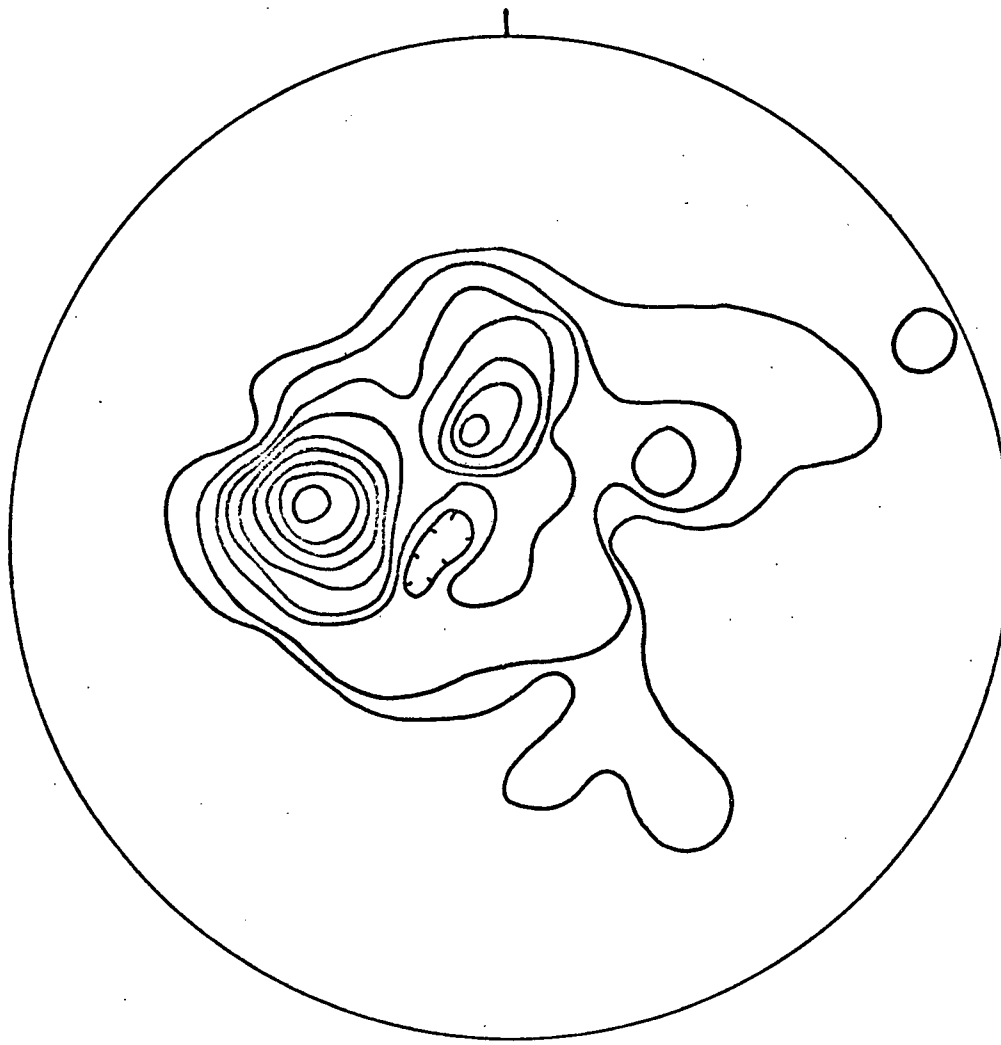


DIAGRAM 25 HORIZONTAL MAX. 19% 100 CRYSTALS

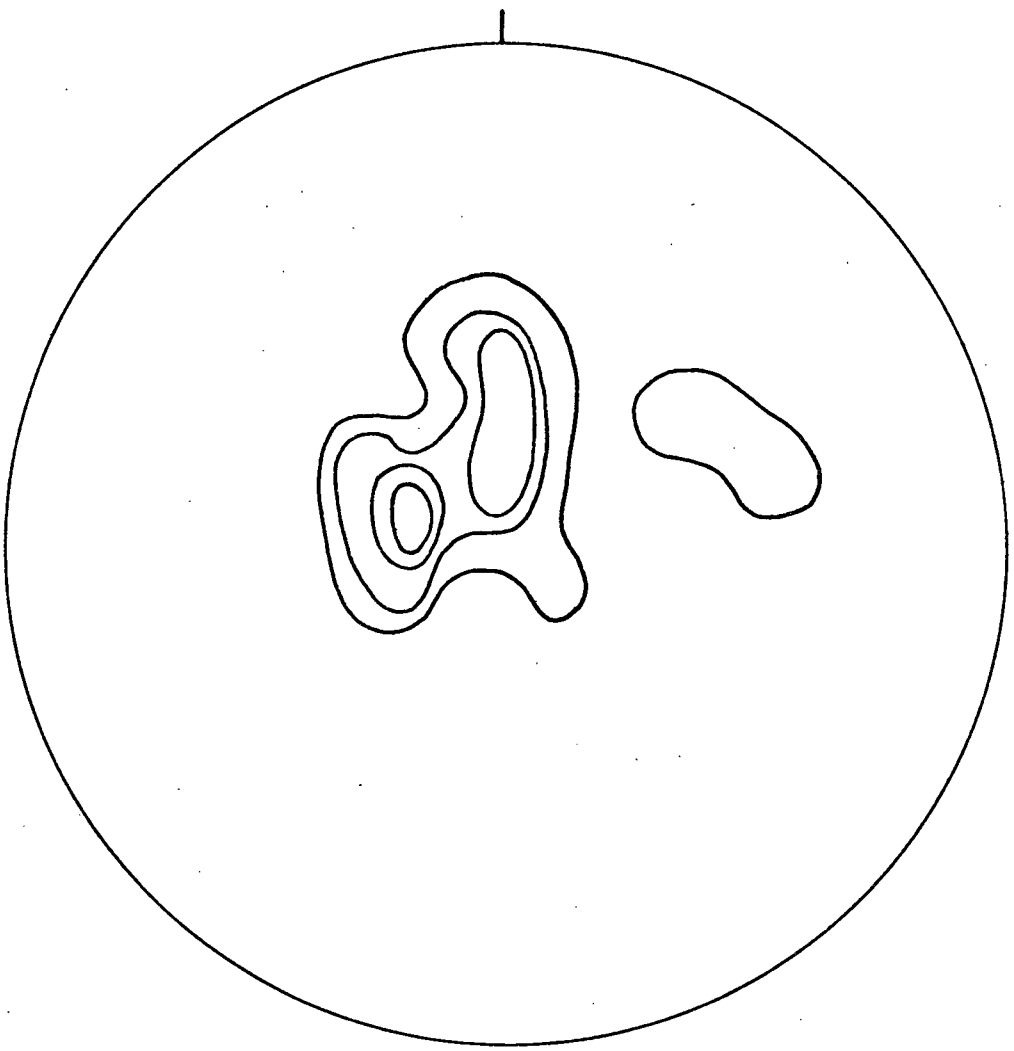


DIAGRAM 26 HORIZONTAL MAX. 6% 40 CRYSTALS

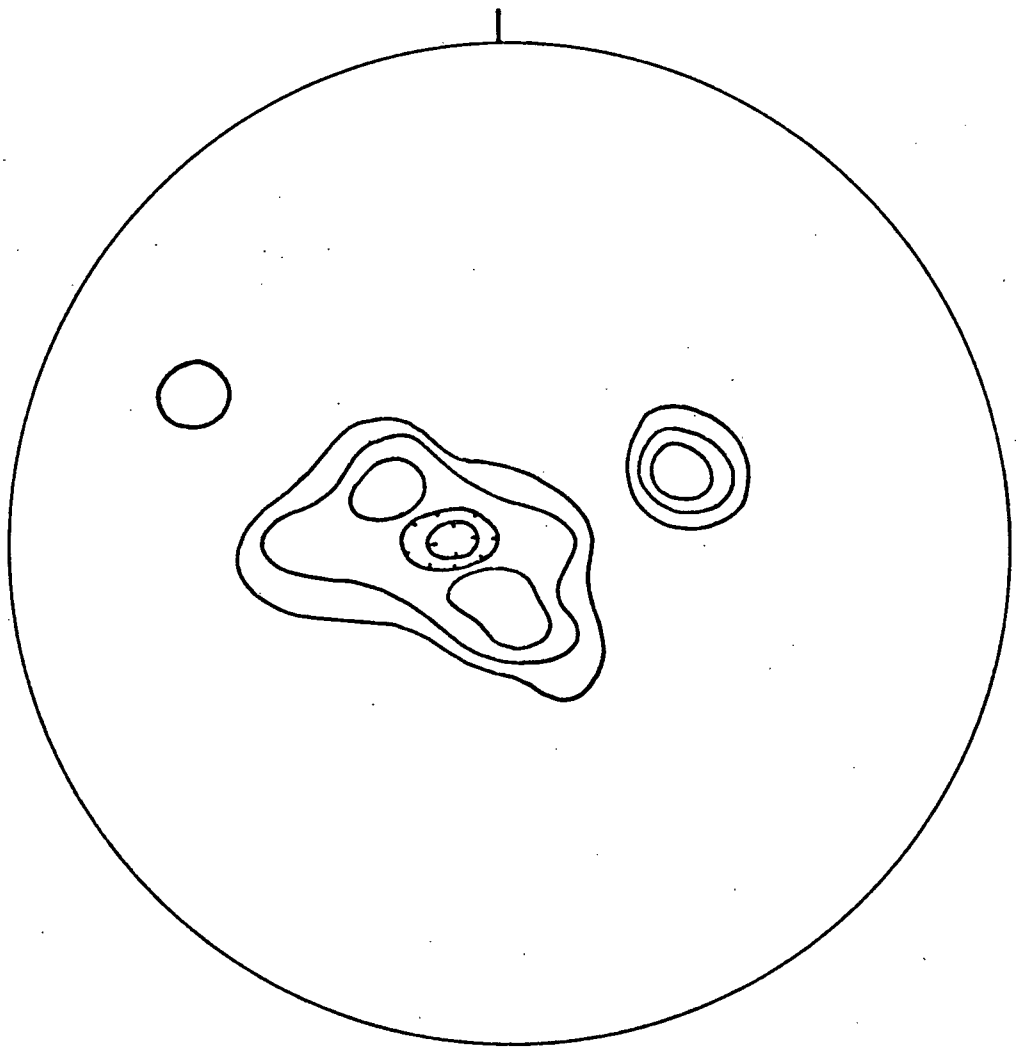


DIAGRAM 27 HORIZONTAL MAX. 4% 30 CRYSTALS

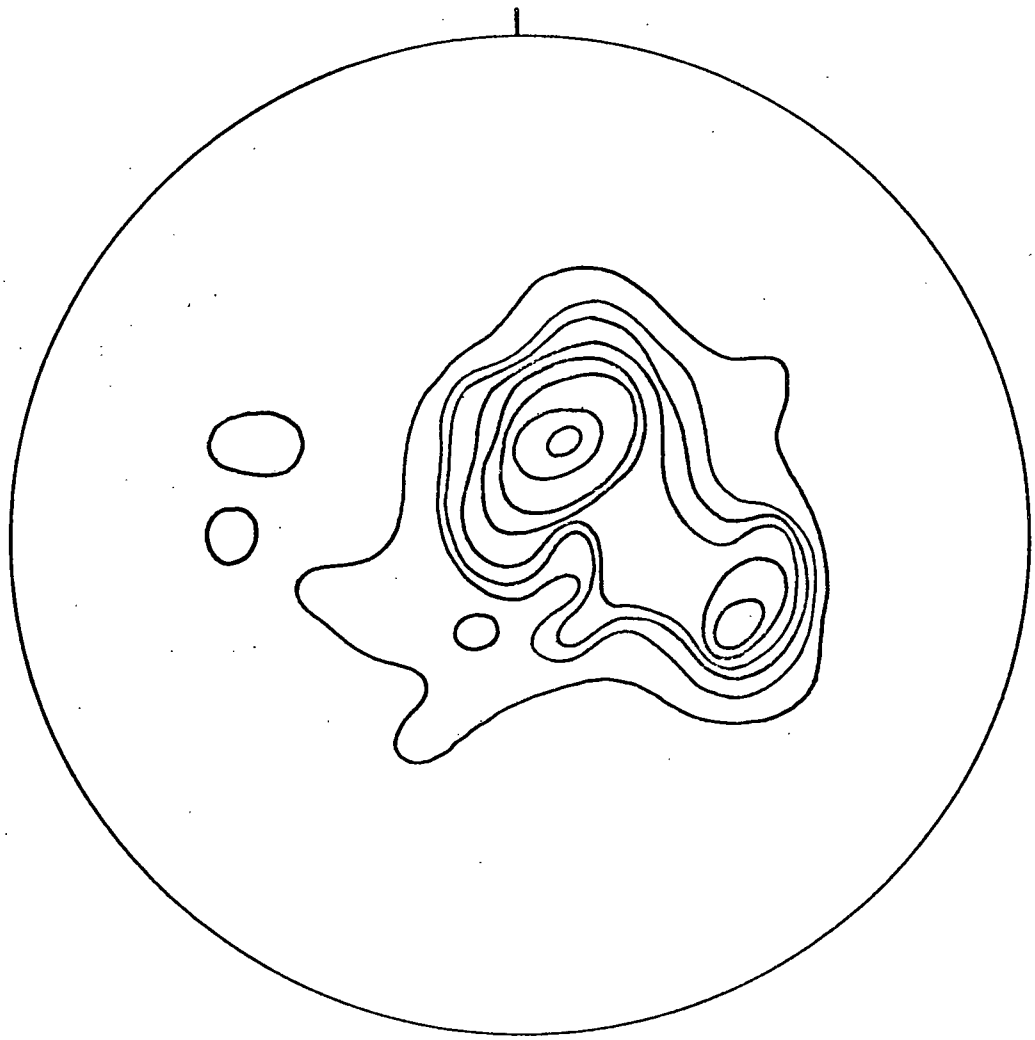


DIAGRAM 28 HORIZONTAL MAX. 16% 250 CRYSTALS

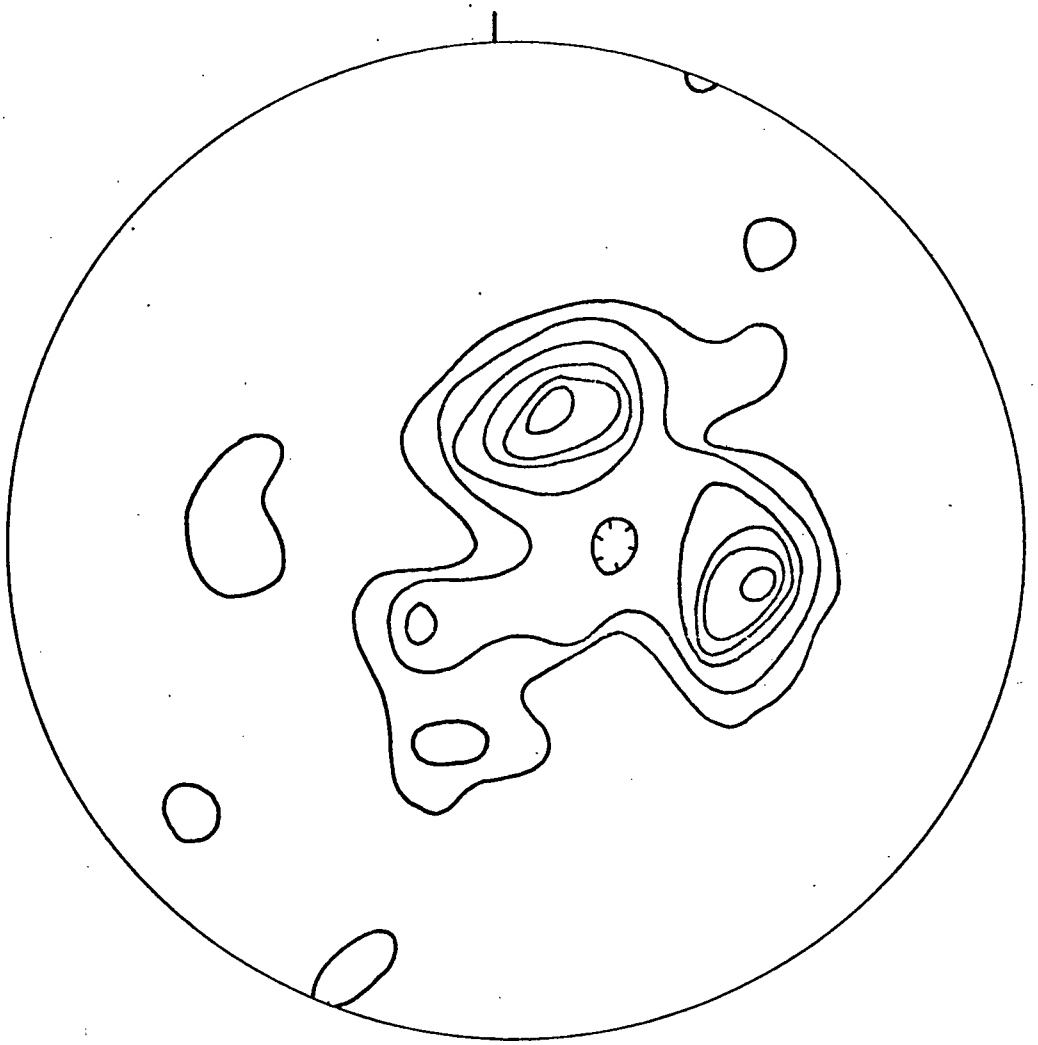


DIAGRAM 29 HORIZONTAL MAX. 12% 130 CRYSTALS

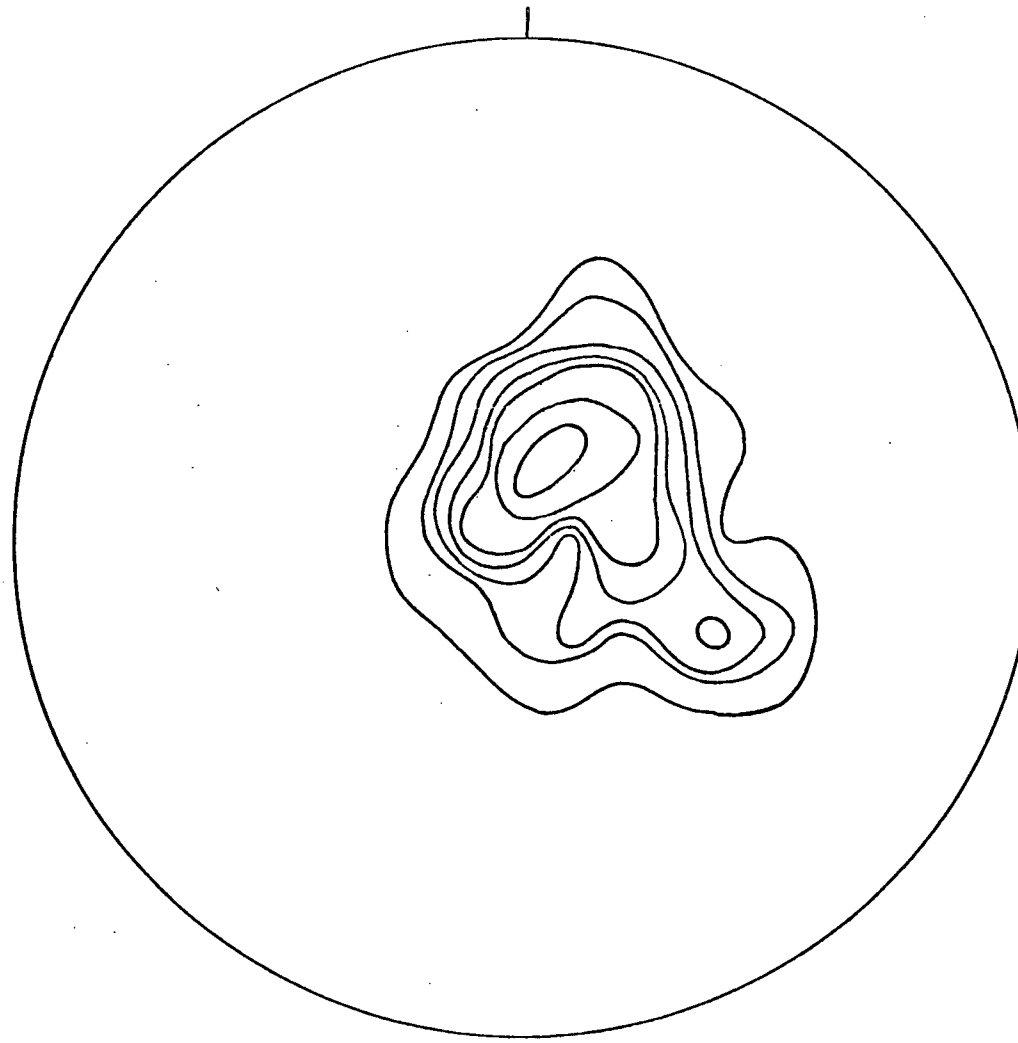


DIAGRAM 30 HORIZONTAL MAX. 14% 120 CRYSTALS

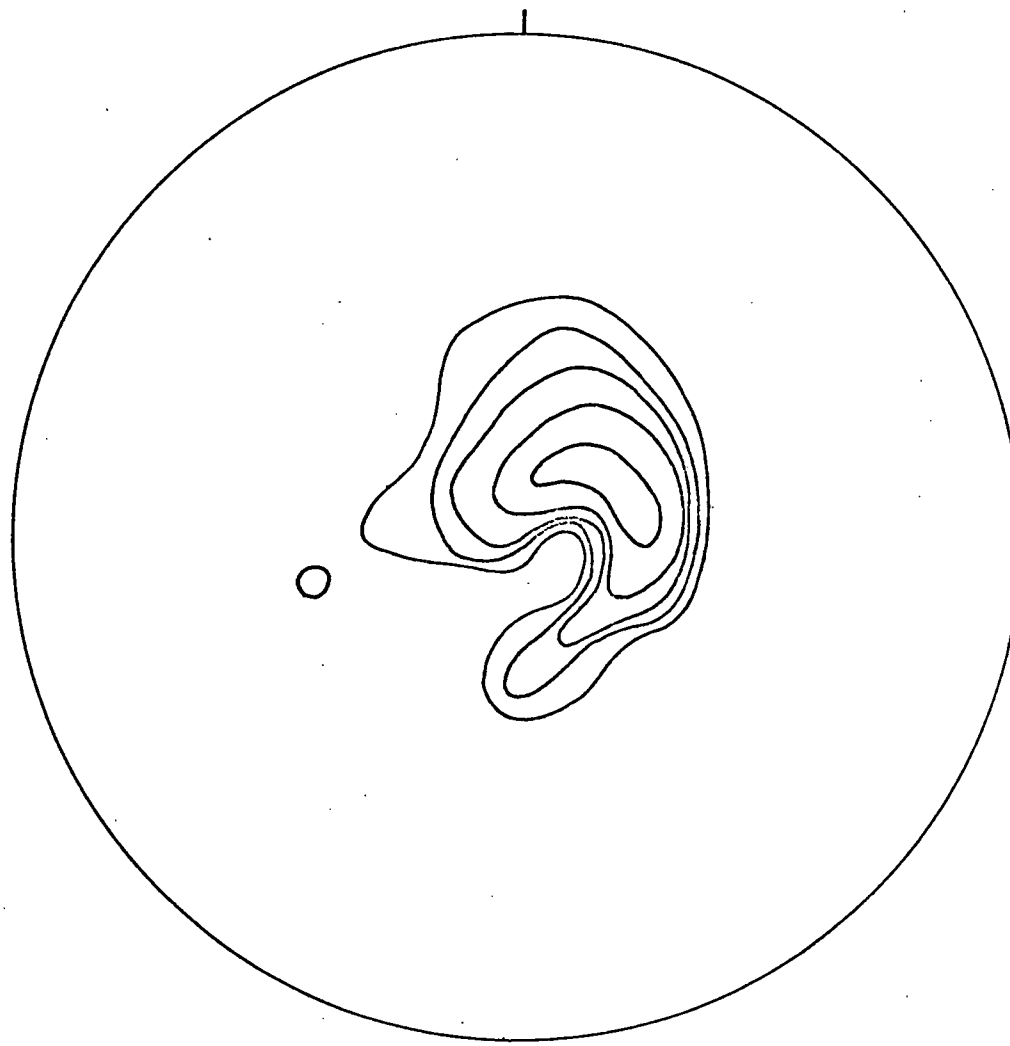


DIAGRAM 31 HORIZONTAL MAX. 9% CRYSTALS IN SEDIMENT

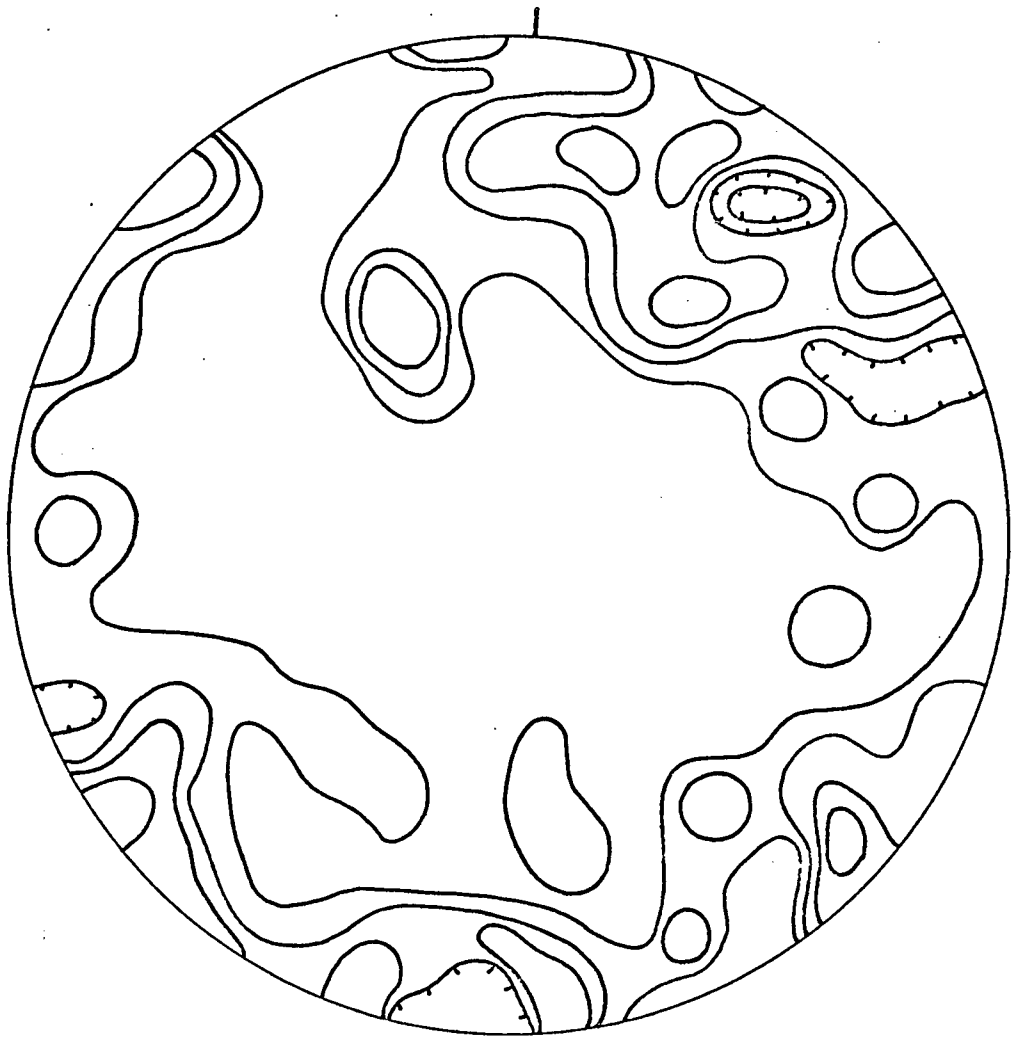


DIAGRAM 32 VERTICAL MAX. 6% 90 CRYSTALS

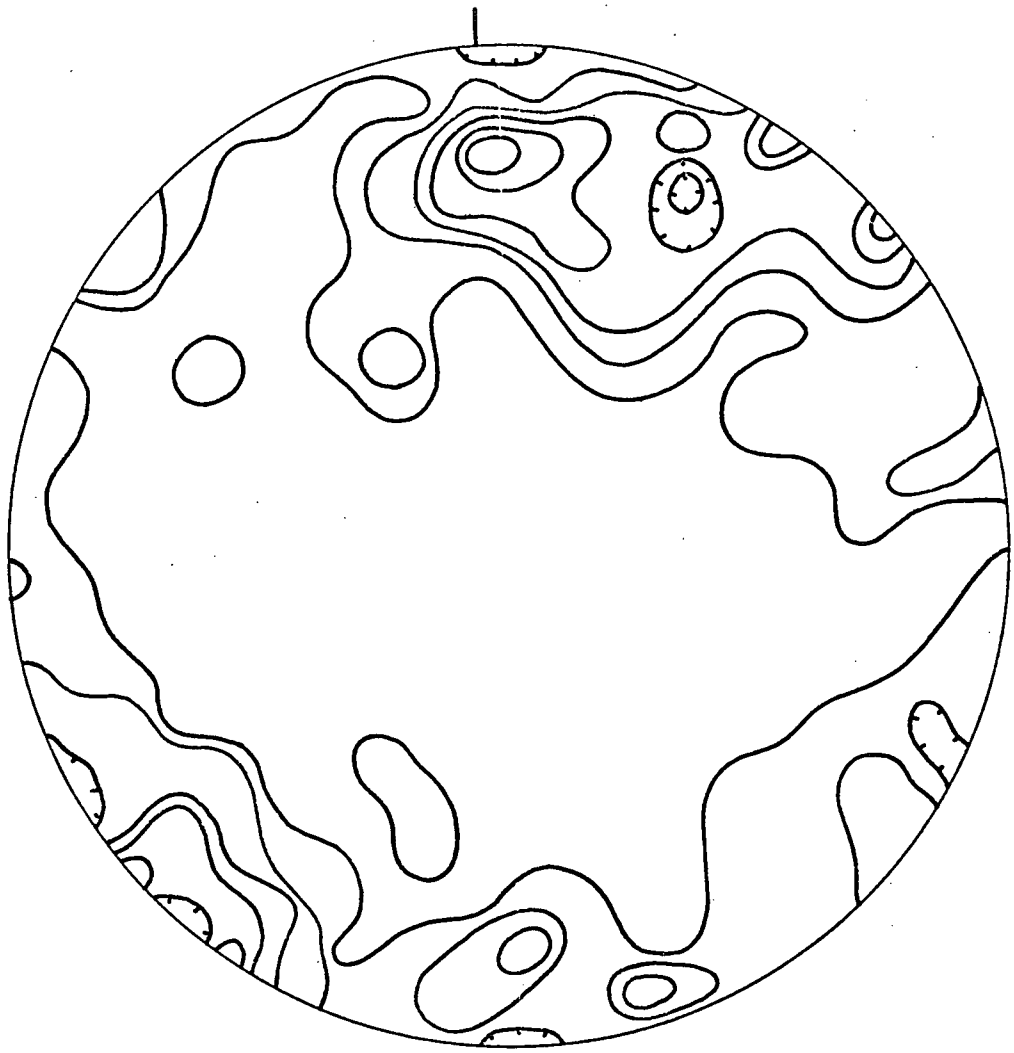


DIAGRAM 33 VERTICAL MAX. 12% 200 CRYSTALS

Plate 1. Style 1 Fold morphology displayed on corridor wall. Wall height is approximately 2 m. Dark bands are ice; light bands are sediment.

Plate 2. Boudin of icy sand in ice. Lighter material is sediment. Knife is 15 cm long.

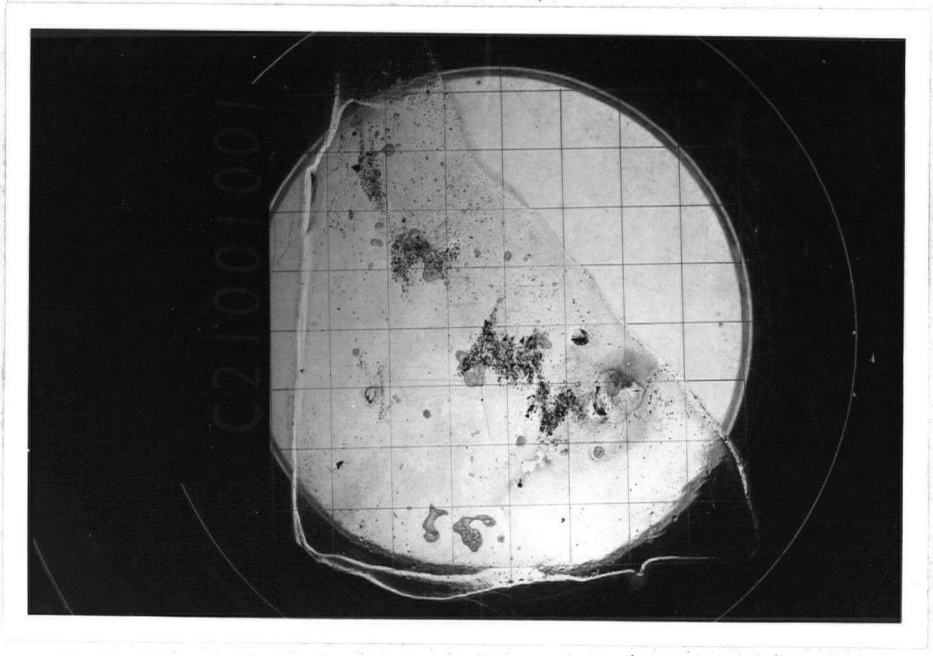


Plate 3. Style 1 Fold. Offsetting of sediment in fold closure. Grid size is 1 cm^2.

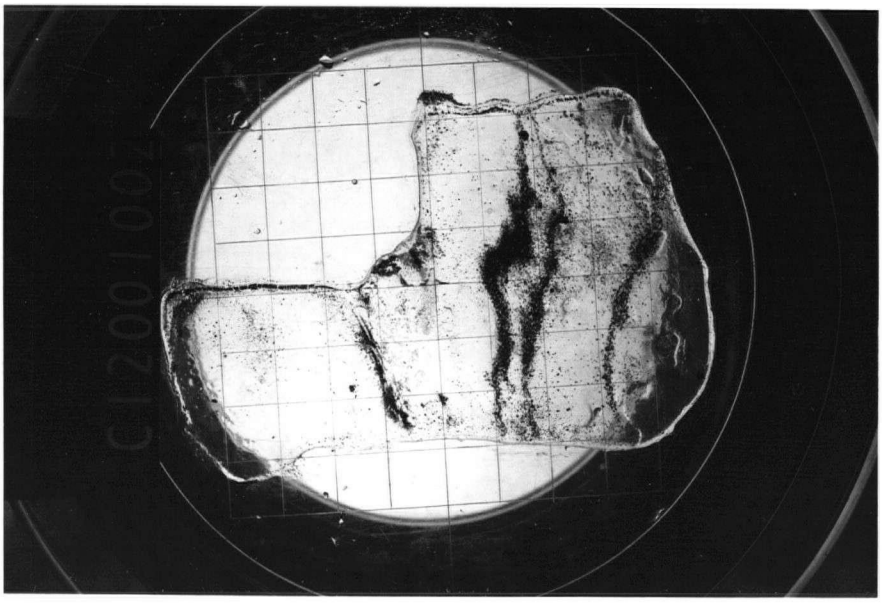


Plate 4. Style 2 Fold. Axial surface is oblique to local foliation.

Plate 5. Etched crystal boundaries showing up as a network of fine lines on cellar wall.