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Structural Geology and Slope Stability of the Southeast Slopes of Turtle Mountain, Alberta

by

Kenneth Wayne Fossey

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Structural Geology and Slope Stability of the Southeast Slopes of Turtle Mountain, Alberta submitted by Kenneth W. Fossey in partial fulfillment of the requirements for the degree of Master of Science in Geology.

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Date 21 April 1986

Dedication

To my wife Lynne and my parents Walter and Adeline for their support and encouragement over the years.

Abstract

Turtle Mountain is in the southern Foothills of the Canadian Rocky Mountains. The Frank Slide occurred on the east face of Turtle Mountain in 1903 and involved approximately 30 million m^3 of Paleozoic carbonates. Recently there has been renewed interest in the stability of Turtle Mountain south of the Frank Slide. This study looks at the structure and the possible modes of failure of South Turtle Mountain.

The major structures present in the study area are the Turtle Mountain Thrust, Turtle Mountain Anticline and the Hillcrest Syncline. The Turtle Mountain Thrust can be divided into two north-south trending segments in the map area: (1) a western, west-dipping segment consisting of a hangingwall flat in the Banff Formation and (2) an eastern horizontal segment consisting of a hangingwall ramp in the overlying strata. In the hangingwall of the Turtle Mountain Thrust the Turtle Mountain Anticline and Hillcrest Syncline end downward against the fault. The Turtle Mountain Anticline is a symmetrical upright non-cylindrical fold whose fold axes have an overall orientation of 190° 10°. The Hillcrest Syncline is an asymmetrical upright non-cylindrical fold with fold axes that trend and plunge at about 180° and 20°, respectively. The western flat occurs beneath the west limb of the Turtle Mountain Anticline and the ramp beneath the common limb of the two folds and the eastern limb of the Hillcrest Syncline.

On south Turtle Mountain the areas of interest with respect to slope stability are defined on the basis of penetrative bedding. The results of toppling and wedge sliding were observed on the west limb of the Turtle Mountain Anticline east of the mountain crest. Pi-diagrams show that planar, wedge and toppling failure are kinematically possible throughout the study area. Back analysis of the Small Slide gave an angle of internal friction of 40° for wedge sliding. The stability of South Turtle Mountain could have been affected by closure associated with the Frank Mine. This closure would have reduced the cohesion of the Rock mass above. Circular failure analysis of an area adjacent to the Frank Slide produced a factor of safety of 1.1 which indicates that the possibility of further failure cannot be ruled out.

Acknowledgements

I would like to express my gratitude to Dr. H.A.K. Charlesworth and Dr. D.M. Cruden for their guidance, encouragement, patience and criticism throughout the course of this study. I would also like to thank Alberta Environment for their assistance in producing the 1:5000 topographic map of the area and for providing the 1983 aerial photographs. In particular I would like to thank Don Prosser for his useful comments and support throughout the study. The Turtle Mountain Archives Inventory produced by Heidi Biberhofer (1983) for Alberta Environment was also of great assistance in my research of the Frank Slide. Desmond Wynne's assistance and guidance with the computer programming and systems is gratefully acknowledged. Finally I would like to thank the other graduate students in structural geology that added so much to the daily work atmosphere, namely Steve Johnston, Brian Klappstein and Sophie Liaudet.

Alberta Environment paid the author's salary during the summers of 1983 and 1984. Other financial support was provided by the University of Alberta in the form of a graduate teaching assistantship and by Dr. Cruden in the form of a bursary.

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1. Introduction

The stratigraphic succession in the Rocky Mountain Foothills consists of an older miogeoclinal sequence dominated by Paleozoic carbonates and a younger clastic wedge sequence. During late Mesozoic and early Cenozoic time these sequences were shortened and thickened by thrusting and folding. The Foothills are characterized by west-dipping thrusts that merge at depth with a basal detachment zone, and by north-south trending folds.

At 4:10 AM on April 29, 1903 a massive rockslide occurred on Turtle Mountain, which lies in a Paleozoic inlier in the Rocky Mountain Foothills of Southern Alberta. Approximately 30 million m^3 of Rundle Group limestone on the top of the mountain slid down destroying half the town of Frank (McConnell and Brock, 1904). Since then there has been concern over the stability of the rest of Turtle Mountain (Brock, 1910; MacKay, 1931).

In 1983 the Research Management Division, Alberta Environment required the geotechnical mapping of Turtle Mountain to be extended in Phase 4 of its monitoring and assessment of the stability of the mountain. The aims of the study undertaken by the author were:

1. to extend the geotechnical mapping of Turtle Mountain to cover the south east slopes including the area over the Frank Coal Mine,
2. to determine the structure of Turtle Mountain south of the Frank Slide,

3. to conduct a study to determine modes and areas of instability on Turtle Mountain south of the Frank Slide.

Data defining the structure of South Turtle Mountain and its relationship to the stability of the east slope were analyzed using computer-based procedures. This is the first time that these computer-based procedures have been used in the assessment of slope stability.

The map area is located in the Crowsnest Pass in southwestern Alberta, 3 km south-east of Blairmore and 1 km south of Highway 3 (Figure 1). The topography rises from 1300 m to 2200 m with a maximum elevation change in the steepest section of 500 m in 750 m. Outcrop is good on the upper slopes and excellent in the gullies. Most covered intervals on the upper slopes are due to rock debris from above. On the lower slopes exposure is poor except in the coal subsidence pits and along ridges.

Coal from the Kootenay Formation in the footwall of the Turtle Mountain Thrust was mined at Frank from 1901 to 1918, first by the Canadian American Coal and Coke Company and later by Franco-Canadian Collieries Ltd. The first drift mine operated from 1901 to 1910 when a mine fire caused it to be abandoned. In 1911 the second drift mine opened 128 m beneath the first and operated until 1918 when operations connected it with the fire in the original mine above and the second mine was abandoned (Sherwin, 1916). Both mines were situated at the foot of Turtle Mountain and

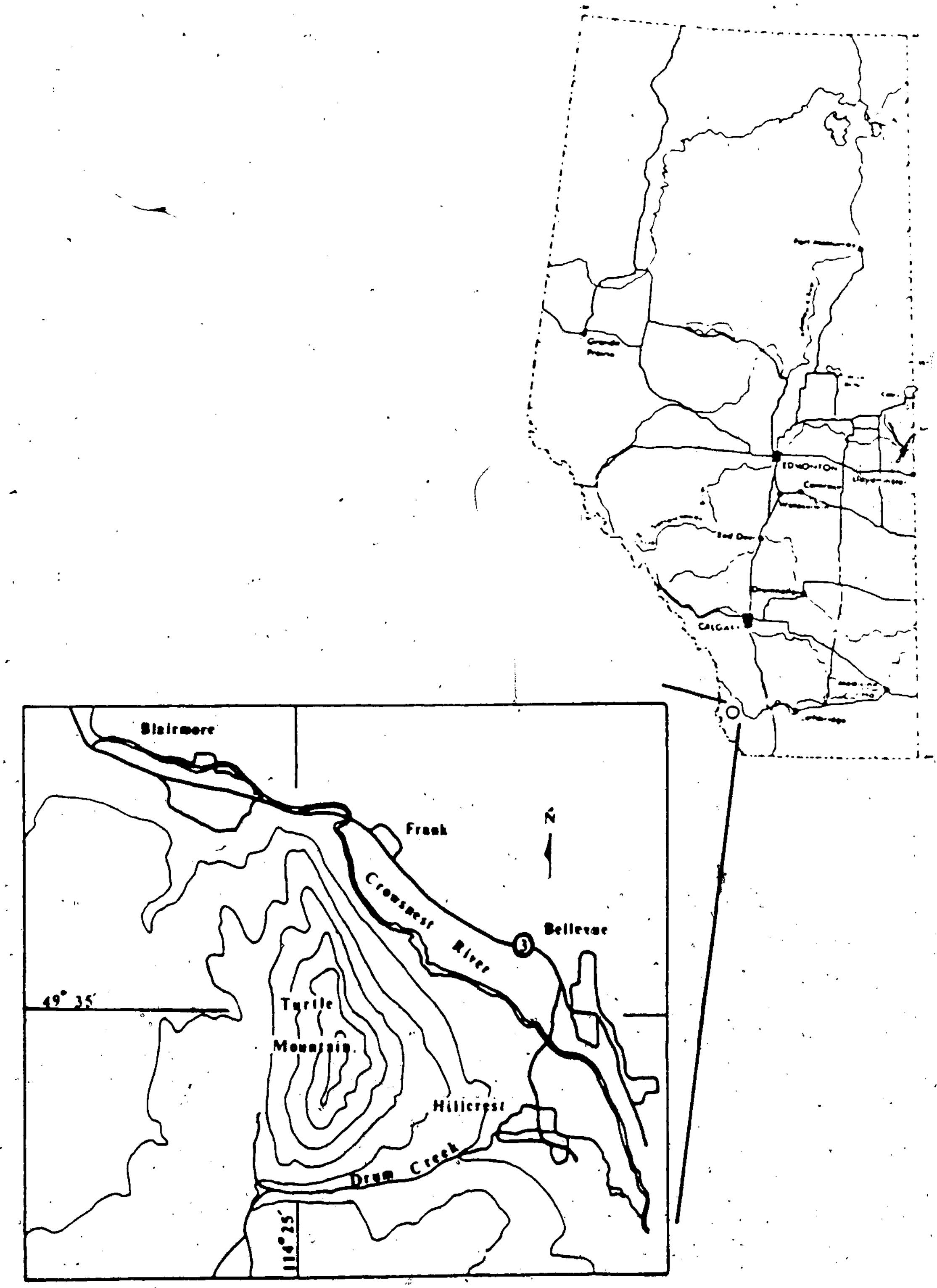


Figure 1. Location Map Turtle Mountain

exploited a nearly vertical coal seam 4 to 4.6 m thick (McConnell and Brock, 1904) with a north-south strike. The southern edge of the Frank Slide corresponds closely to the limits of the large chambers of mined coal. Closure of these workings may have been one of the main contributing factors in triggering the slide (McConnell and Brock, 1904; Allan, 1933).

Coal was also mined by Hillcrest Collieries Ltd. in the hangingwall of the Turtle Mountain Thrust. This mine caused subsidence in the overlying Cretaceous strata on the lower slopes of Turtle Mountain.

Turtle Mountain has been the subject of many geological studies. McConnell and Brock (1904) were the first to study the mountain after the slide. They reported to the Canadian Government in June, 1903 that the main factors causing the Frank Slide were:

1. the structure of Turtle Mountain,
2. heavy precipitation in recent years,
3. heavy frost action on the morning of the slide,
4. major earthquake tremors in 1901,
5. closure of the Frank Mine at the base of Turtle Mountain.

The main contributing factor was stated to have been the structure of the mountain which they described as a highly fractured and jointed monocline of limestone (McConnell and Brock, 1904, p. 17) in which failure had occurred along joint planes that cut across bedding. Nine cross-sections drawn in 1912 (Daly et al., 1912) supported this erroneous interpretation of the structure of Turtle Mountain as a monocline.

The Turtle Mountain Anticline was recognized by Leach (1904) and Mackenzie (1913). The 1:63,360 Geological Survey of Canada map of Blairmore included four cross-sections of Turtle Mountain depicting the Turtle Mountain Anticline (Rose, 1920).

Concern over the stability of the north peak of the mountain was expressed in a report to the commission appointed to investigate the condition of Turtle Mountain (Brock, 1910). A map of Turtle Mountain at a scale of 1:9,600 was drawn by W. H. Boyd to show the extent of the instability of the North Peak (Daly, 1912). As a result of this study the town of Frank was relocated to the northeast, away from the mountain.

MacKay (1931) renewed interest in Turtle Mountain by describing the south peak as an unstable pyramid of rock, 100 m high, bound at the back by fissures. He also recognized that the structure of Turtle Mountain was more complex than a simple anticline (MacKay, 1933). J.A. Allan was retained by the Alberta Government in 1931 to investigate the concerns raised by MacKay. Allan produced three reports (1931, 1932, 1933) on the geology and stability of Turtle Mountain. He stated that frost action, mine subsidence or earthquake activity might have triggered another slide and (Allan, 1931, p. 13) estimated that an additional 45,000 m^3 of rock had fallen since 1903, mostly in small blocks (Allan, 1932). He stated that extraction of coal from the Frank Mine was the cause of the Slide (Allan, 1933, p. 3) and he also expressed concern about the effect of collapse of the mine workings on the stability of the south peak of Turtle Mountain (Allan, 1932, p. 22). In 1933 he established 18 monitoring stations in fissures at the top of the mountain to measure movement. The elevations of the three peaks on Turtle Mountain were established at this time by the Geodetic Survey. Recommendations were made that aerial photographs be taken of Turtle Mountain, seismometers be installed to monitor earthquake activity, and the highway be moved farther from the slide (Allan, 1933, p. 27-28). Although the highway was moved, the other two recommendations do not appear to have been implemented.

D.K. Norris (1955) produced a preliminary 1:63,360 map of the Blairmore area which included Turtle Mountain. A cross-section was drawn through Turtle Mountain showing the Turtle Mountain Thrust and Anticline. The thrust was depicted dipping about 30° to the west. A re-evaluation of Turtle Mountain from an engineering slope stability point of view was begun by Cruden and Krahn (1973). They classified the Turtle Mountain fold as a flexural slip fold and suggested that the kinematically active fabric elements of the slide were bedding, joints and a minor thrust at the toe. Krahn (1974) determined the bedding plane coefficient of friction for the rocks that had failed. An analysis of the mechanisms of failure was carried out using a limit equilibrium method and the factor of safety determined to be close to one (Krahn and Morgenstern, 1976). Crack gauges were installed in fissures at the top of the mountain in 1980 (Cruden et al., 1982). The most recent study of Turtle Mountain was conducted in 1982 as a precursor to this study. It examined the area around the south peak of Turtle Mountain and predicted possible modes of ground movement which included bedding plane sliding and toppling (Cruden, 1983). Automatic seismic recorders were then installed on the mountain and continuous telemetered monitoring of these recorders is underway.

2. Stratigraphy

A. Introduction

Strata ranging in age from Mississippian to Early Cretaceous are exposed in the map area on Turtle Mountain. The stratigraphic column is shown in Table 1. The oldest rocks, exposed in the core of the Turtle Mountain Anticline, belong to the Upper Member of the Livingstone Formation of the Rundle Group. In the hangingwall of the Turtle Mountain Thrust, strata from the Rundle Group form the resistant steep upper slopes of Turtle Mountain and are overlain by the Rocky Mountain Formation, Fernie Group, Kootenay Group and Blairmore Group. In the footwall, nearly vertical Kootenay and Blairmore strata are exposed. Line D - D' on Figure 11 shows the location of a lithologic section measured adjacent to the Frank Slide by the author. This is the area of primary interest in our study due to the possible instability of Paleozoic carbonates. Table 2 gives a summary of the lithologic section contained in Appendix 1.

B. Rundle Group

Mississippian platform carbonates in the Rocky Mountains were first divided by McConnell in 1887 into the Lower Banff Shales and Upper Banff Limestones. The Upper Banff, renamed the Rundle by Kindle in 1924, was raised to group status by Douglas in 1958. He named three new formations within the Rundle namely the Livingstone, Mount Head and Etherington (MacQueen and Bamber, 1968).

Era	System	Series	Group	Formation	Member
MESOZOIC	CRETACEOUS	Upper			
		Lower	Blairmore	Upper	
				Lower	
				Cadomin	
			Kootenay	Elk Mist Mtn. Morrissey	
	JURASSIC	Upper			
		Middle	Fernie		
		Lower			
	TRIASSIC	Upper			
		Middle			
		Lower			
PALEOZOIC	PERMIAN			Rocky Mountain	
	PENNSYLVANIAN				
	MISSISSIPPIAN	Upper	Rundle	Etherington	Upper Middle Lower
				Mount Head	Carnarvon Marston Loomis Salter Baril Wileman
		Lower		Livingstone	Upper

Table 1. Stratigraphic column (after Bamber et al., 1981)

System	Group	FORMATION	MEMBER	DESCRIPTION
MISSISSIPPIAN	RUNDLE GROUP	Etherington	Middle	Medium bedded, fine grained, argillaceous and dolomitic limestone with intermittent vuggy and cherty intervals. Interbedded calcareous and argillaceous dolomite near bottom. (83 m)
MISSISSIPPIAN	RUNDLE GROUP	Etherington	Lower	Interbedded; calcareous siltstone shale, dolomitic argillaceous limestone, and medium bedded, fine crystalline, medium grey, argillaceous dolomite. (63 m)
MISSISSIPPIAN	RUNDLE GROUP	Mount Head	Carnarvon	Medium to thinly bedded, fine to very fine grained, grey, crinoidal limestone with intermittent vuggy and cherty intervals. (63 m)
MISSISSIPPIAN	RUNDLE GROUP	Mount Head	Marston	Medium to thickly bedded, fine crystalline, dark grey, calcareous dolomite interbedded with fine grained dolomitic limestone. (11 m)
MISSISSIPPIAN	RUNDLE GROUP	Livingstone	Upper	Massive to thinly bedded, medium grey course grained, crinoidal limestone with dolomitic sections and irregular chert blebs and stringers. Pitted vuggy intervals throughout. (84 m)

Table 2. Summary of lithologic section.

The depositional and early diagenetic environment suggested for the Rundle Group in southwestern Alberta (Macqueen et al, 1972) is a broad, stable, slowly-subsiding, marine carbonate platform adjacent to the emergent, low-relief craton. This depositional environment accounts for lateral variations within the formations. The relative position of the shoreline dictated the type of sediment deposited.

Livingstone Formation

The Livingstone Formation was divided into two lithostratigraphic units (Douglas, 1958) named the Upper and Lower Members. Coarse, crinoidal limestone alternating with thinly-bedded, medium-fine crystalline limestone form the Lower Member. The Upper Member contains mainly thickly-bedded or massive, coarse, light-grey, crinoidal limestone alternating with thinner interbeds of dolomite or silty dolomite. These rocks originated in open marine to shallow echinoderm-bryozoan shoals on a marine carbonate platform.

In the lithologic section shown in Appendix II, only the Upper Member of the Livingstone is present, and is represented by 84 m of coarse grained, medium grey, resistant, crinoidal limestone with irregular chert blebs and stringers interbedded with fine crystalline dolomitic limestone. The contact with the Mount Head Formation is drawn at the first recessive unit below the cliff forming Upper Livingstone limestone (Price, 1965).

Mount Head Formation

The Mount Head Formation conformably overlies the Livingstone and has been divided into six members in the Rocky Mountain Front Ranges (Douglas, 1958). More abundant shallow marine echinoderm-bryozoan limestones alternate with supratidal dolomites, due to repeated transgressions and regressions of the shoreline. These alternating lithostratigraphic units form the six members of the Mount Head Formation. The supratidal sediments represented in the Wileman, Salter and Marston Members are composed of recessive yellowish-brown dolomite and micritic limestone. These alternate with the shallow marine, resistant, skeletal and micritic limestones of the Baril, Loomis and Carnarvon Members (Bamber et al., 1981). Lateral facies changes and thrusting in the Front Ranges have complicated recognition and correlation of the Mount Head strata away from its type section (MacQueen and Bamber, 1968). In the Foothills the Mount Head is undivided peritidal dolomite and solution breccia. Alternation of shallow marine carbonates and supratidal carbonates form the six members in the Front Ranges. To the west the lower four members pass laterally into coequivalent echinoderm-bryozoan limestone included in the Livingstone Formation (Price, 1965).

All six Members of the Mount Head were observed in the footwall of the Turtle Mountain Thrust 8 km north of the map area (Norris, 1955). To the northwest, in the

Highrock Range of the Front Ranges, the Mount Head is divisible into only two units, an Upper and a Lower Limestone (Macqueen and Bamber, 1968).

On Turtle Mountain only two lithostratigraphic units were recognized. The lower 11 m are thick to medium bedded, fine crystalline, recessive, fossiliferous, calcareous dolomite, alternating with fine crystalline limestone. This unit equates well with the description of the Marston Member, a recessive sequence of fine crystalline limestone alternating with silty dolomite (Price, 1965). Above the Marston are 63 m of medium to fine bedded, medium crystalline limestone at its base, grading into fine to very fine crystalline limestone at the top. Irregular chert nodules and argillaceous limestone are interspersed throughout the Carnarvon. This description compares well with the one given by Price (1965) for the Carnarvon Member as a fine-medium bedded, fine to very fine crystalline limestone with skeletal calcarenite, isolated irregular chert and rare dolomite. The lower four members of the Mount Head cannot be distiguished, having undergone a facies change to coarse-grained crinoidal limestone, and are included in the Upper Livingstone Formation.

Etherington Formation

At the top of the Rundle Group, the Etherington Formation conformably overlies the Mount Head and is the stratigraphic interval between the fine crystalline limestone of the Mount Head Formation and the quartzose sandstones of the Rocky Mountain Formation (Price, 1965). Douglas (1958) defined three lithostratigraphic units, namely the Lower, Middle and Upper Members.

The Lower Member consists of alternating (a) medium to coarse crystalline silty limestone, (b) fine crystalline, thin bedded, yellowish grey, limestone and dolomite, and (c) light green shales (Price, 1965). Light grey skeletal limestone makes up most of the Middle Member, with subordinate fine crystalline dolomite and limestone occurring throughout. The Upper Member is mainly composed of finely laminated and cross-bedded dolomite with some large dolomite aggregates (Douglas, 1958).

On Turtle Mountain only the Lower and Middle Members are present (Appendix 1). The Lower Member is 63 m thick, consisting of fine to medium bedded, fine to very fine crystalline dolomite with interbedded limestone at the bottom. Towards the top, the dolomite grades into interbedded siltstone, yellowish grey, thin bedded, silty limestone and dolomite, and calcareous shale. Above a sharp contact are 83 m thick of medium bedded calcarenite and minor fine crystalline dolomite which correlate with the Middle Member of the Etherington Formation.

C. Rocky Mountain Formation

The Rocky Mountain Formation disconformably overlies the Etherington. It is composed of thin, flaggy to blocky, quartz, calcareous, and cherty sandstone beds (Douglas, 1958). These beds are poorly exposed in the map area.

Their thickness, estimated from cross-section A - A', is 50 m.

D. Fernie Group

Recessive strata of the Fernie Group which disconformably overlies the Rocky Mountain are composed mainly of dark grey to black shales which in places are calcareous, arenaceous, and slightly bituminous. In the map area only two outcrops of dark, slightly calcareous shale were encountered. The Fernie Group is approximately 130 m thick in section C-C'.

E. Kootenay Group

In the Crowsnest Pass area the Kootenay Group conformably overlies the Fernie Group and is unconformably overlain by the Blairmore Group. The Kootenay is composed of cyclically alternating siltstones, medium to fine grained, cross-bedded sandstones, silty shales, and thick bedded and cross-bedded, course-grained sandstones. It contains three major coal seams. These sediments were deposited by delta progradation after uplift of the source terranes to the southwest in the Late Jurassic (Jansa, 1972). Outcrops in the map area are of medium- to fine-grained, cross-bedded sandstone. Norris (1955) estimated the thickness of the Kootenay Formation in the map area to be between 137 m and 167 m.

F. Blairmore Group

The Blairmore Group consists of sandstones and sandy shales. At its base is the Gadomin Formation, a conglomerate which lies on a sharp erosional contact with the Kootenay Group. The thickness of the Blairmore Group is 760 m (Norris, 1955).

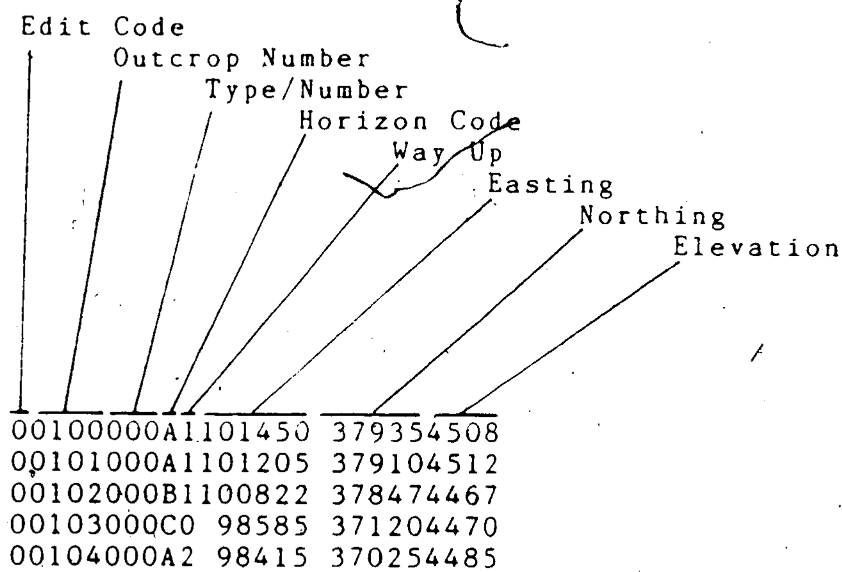
3. Data Collection

Outcrop data were collected in the field by visiting outcrops, plotting positions on 1:5,000 aerial photographs, determining elevations using an aneroid altimeter, and recording the structure and stratigraphy. In preparation for computer processing all location and some geological information was transferred onto data sheets. Lithologic information gathered at outcrops was used to trace stratigraphic contacts on aerial photographs.

Data from the mine plans, field work and other sources were all compiled using the digitizing tablet into the proper format for input into the software package TRIPOD (Charlesworth, 1981) as shown in Figure 2. TRIPOD was then used to process the data and produce numerical and graphical output. The data files used in this project were stored in the file Fossey on computer tape number 0070555 at the University of Alberta by Dr. Charlesworth.

Transportation to and from the field area, and on the lower slopes of the mountain was by means of a Suzuki RV90 motorcycle. The remainder of the mountain was covered on foot. Three sets of aerial photographs were supplied by the Alberta Department of the Environment for use in field mapping. The first set (AS 2411 #247-#250) gave stereoscopic coverage of the top of Turtle Mountain on a 1:5,000 scale. The second (AS 1178 #202) was a 1:5,000 enlargement of a 1:21,120 scale aerial photograph which was used to map Cretaceous strata on the lower slopes of the

File A



File B

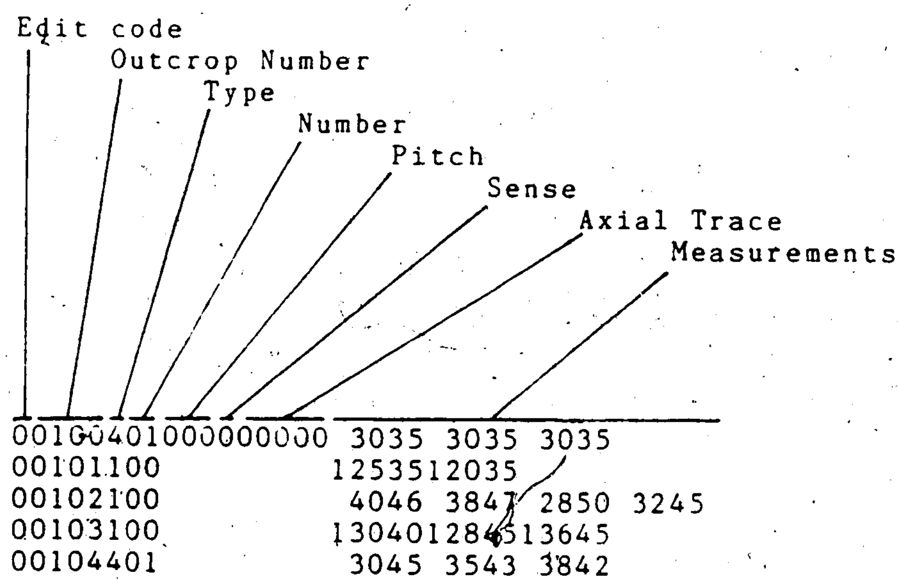


Figure 2. Format for Input Files A and B (TRIPOD).

mountain. The third set (AS 2850 #253 & #254), flown on September 27, 1983 after the end of the field season, gave stereoscopic coverage of the map area at a scale of 1:15,000. The third set was used to trace the stratigraphic contacts and consolidate the data collected using the older photographs.

The elevation of each outcrop in meters was calculated from aneroid altimeter readings taken in the field. The computer program listed in Appendix 2 was used to adjust the elevation for temperature variations. Attempts were made to use an aneroid barograph base station to aid in adjusting for barometric pressure changes throughout the day. The results proved unsatisfactory due to the distance of the barograph from Turtle Mountain and the highly localized weather patterns in the Crowsness Pass area. As a result, the computer program in Appendix 2 gives only a linear adjustment for barometric changes between the first reading of the day and the last. Elevation accuracy after adjustment is estimated at 2 m. This estimate was obtained by making repeated vists to a location of known elevation on different days.

A topographic base map of the area was prepared by North West Survey Corporation International on a 1:5,000 scale for the Alberta Department of the Environment. The base map was prepared using points surveyed in by the Survey branch of Alberta Environment which was tied into the Geodetic Survey of Canada and the 1983 1:15,000 aerial photographs. This map is 11 km square with contours every 2.5 m. This map was essential in the present study as the only other recently published topographic map of the area is a 1:50,000 NTS map (82 G/9, Blairmore, Alberta). The base map was not completed until three months after the end of the field season. The location of each outcrop on the base map was determined using notes of outcrop location, elevation measurements, and locations marked on 1:5,000 aerial photographs. From the base map the easting and northing of each outcrop referred to an origin within the map were obtained using the digitizing tablet. The elevation of each data point was also entered using the digitizing tablet (see Appendix 3). These coordinates are necessary for input of field data into the computer package TRIPOD. The origin has UTM coordinates in meters of -40000E, 5490000N, and an elevation of mean sea level.

A. Mine Data

Copies of the mine plans of the original Frank mine owned by the Canadian Coal and Coke Consolidated Company Ltd. were obtained from the Glenbow Museum in Calgary (File 0S1-0S47 & F1-f23) and the Provicial Archives in Edmonton (Mine Plan #48). These plans date from 1910 and 1918 and have a scale of 1:2,400. Also a composite plan and elevation of both mines at a scale of 1:5,000 was obtained. The 1918 mine plans include thirteen locations indicating the orientation of the main coal seam in the mine. These data were recorded and the locations transferred to the

1:5,000 composite mine plan. Cross-sections on the 1910 mine plans allowed faults to be located and plotted on the composite mine plan. Legal Sub-Division lines were drawn on the composite mine plan which allowed localities on it to be transferred to the topographic base map. The elevation of the mine entrance was determined from its location on the topographic map as there was no mention of elevation on the mine plans or in any of the records. The structural data were transferred onto data sheets (Figure 2) in preparation for computer storage and processing. The location of each data point was obtained by defining four common points on the base map and composite mine plan and using the digitizing tablet as described in Appendix 3 and below.

B. Other Data

Structural data on the south peak of Turtle Mountain were collected in June of 1983 by P. McLellan for the Research Management Division of Alberta Environment in Phase 3 of the Turtle Mountain study. Bedding had been plotted on a 1:500 geological map of the South Peak of Turtle Mountain. Forty one dip directions and dips in the Rundle Group were recorded. These data were incorporated in the present study using the digitizing tablet, as described below, by establishing three points on both the 1:500 map and the topographic base map. Joint data recorded by P. McLellan in field notes were placed in a computer file for processing using the ORIENT program (Charlesworth, 1984).

C. Digitizing Tablet

Data from maps were placed into preliminary computer files using a Tectronix 4954 digitizing tablet and a Tectronix 4016-1 graphics terminal. The structural, locational, and stratigraphic information were acquired from the maps using computer programs written by Desmond Wynne and Dr. H.A.K. Charlesworth. Instructions for the use of the digitizing tablet and these programs are outlined in Appendix 3.

The Tectronix 4954 digitizing tablet recognizes different locations on its tablet. When the graphics cursor is activated at a point on the tablet the tablet location of the cursor is stored. Three procedures using the above programs take structural data off maps and place them in computer files in the proper format for use by the software package TRIPOD. The first procedure, in the initial tablet set-up stage, relates all tablet locations to the map's coordinate system. This is done by entering the maximum and minimum coordinates of the map and then using the cursor to input the tablet location for these points. The program used then converts any point on the digitizing tablet to the coordinates of the map being used. This allows the easting and northing of any data point on the map to be entered directly into a computer file. The remaining information about the data point, such as structural attitude and stratigraphic location, is entered from the digitizing tablet using the menu shown in Figure 3.

This menu is located at the edge of the digitizing tablet and its location is referenced with respect to map coordinates in the set-up procedure. Activation of the cursor after the set-up on any of the boxes on the menu will cause the map coordinates of the box to be stored in a file. This location will be interpreted later as the symbol in the box. All information about a data point can thus be entered into a file from the digitizing tablet.

The second procedure uses this file of map coordinates as input and interprets the raw data as either the easting and northing of a data point on the map or an information symbol from the menu related to a data point. The programs used then write the map coordinate or symbol in a second file which can then be viewed and edited to correct any errors. This second file in turn is used as input into the third procedure which writes two files in the form of field sheets A and B which can be used as input into the software package TRIPOD.

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ELEVATION	4	T	t
[illegible]	5	U	u
[illegible]	6	V	v
[illegible]	7	W	w
[illegible]	8	X	x
[illegible]	9	Y	y
[illegible]	:	Z	z
TYPE	;	[	{
[illegible]	<		|
	=	]	}
	>		~
WARNING	?	_	

Figure 3. Structural Menu Digitizer.

4. Data Storage, Retrieval and Processing

After using the digitizing tablet the data were in computer files in the proper format to be stored, retrieved and processed using the Fortran package TRIPOD (Charlesworth, 1981). This is a command driven, interactive package which produces output in both numerical and graphical form. TRIPOD was designed for use by a field geologist working in sedimentary terranes of orogenic belts.

Data in the computer files are read by the program and placed in digital form in master files. All or any part of the data may then be retrieved and processed in a way specified by the user. In this study TRIPOD was used to produce numerical output in the form of domain statistics and high density equal area pi-diagrams. Graphical output in the form of cross-sections and maps was also produced. For a more complete description of the use of the TRIPOD program refer to Gagnon (1982).

A. Domains

Numerical computer-based techniques were used to divide the study area into domains where the folding is cylindrical. For slope stability analysis, domains were created where bedding had a constant orientation and uniform lithology.

Macroscopic Fold Axes

Fold axes were determined for each domain by using TRIPOD to calculate eigenvalues and associated eigenvectors of a symmetrical 3x3 matrix of summed directional cosines of the bedding normals in each domain. The fold axis orientation was obtained from the eigenvector associated with the minimum eigenvalue (see e.g. Cruden, 1968). The mean bedding orientation in kinematic domains was estimated by the eigenvector associated with the maximum eigenvalue (see e.g. Cheeney, 1983, p. 121). Equal-area pi-diagrams for each domain were also prepared at this time. A program written by the author to give an equal area pi-diagram with a large number of counting locations for the kinematic study is listed in Appendix 4. It is now a subroutine in the TRIPOD package (Charlesworth, 1981) and ORIENT in house software packages (Charlesworth, 1984).

Structural Domains

Initially domains were estimated by inspection and the boundaries drawn perpendicular to the overall trend of the fold axis of the Turtle Mountain Anticline. This orientation was estimated using all bedding orientations in the Rundle strata. Using the DOMT command in TRIPOD, statistical tests (Cruden, 1968; Charlesworth et al., 1976) were carried out on the bedding orientation data to aid in the determination of the cylindricity of a domain. In a cylindrically folded domain the poles to bedding fall on the plane perpendicular to the fold axis. In TRIPOD the

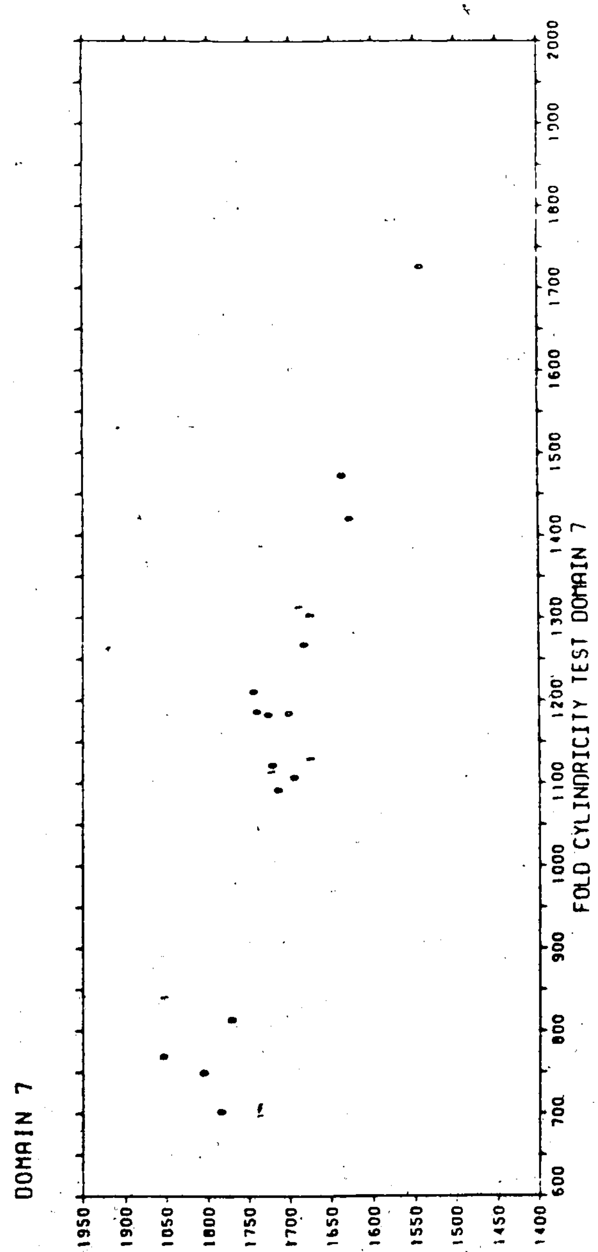


Figure 4. Domain Test Map (TRIPOD).

standard deviation of each bedding normal from the plane perpendicular to the fold axis can be plotted on a map (see Figure 5). This map aids in the detection of spurious data and in establishing domain boundaries. If an area was found not to be cylindrically folded it was redefined by inspection and tested again. Eventually the cylindrically folded domains shown in Figure 5 were obtained.

For the purpose of structural analysis the map area was divided into two parts along a straight line approximating the trace of the contact between the Rundle Group and the Rocky Mountain Formation. The Rundle strata were subdivided into 11 domains the boundaries between which are perpendicular to the overall trend of the Turtle Mountain Anticline and Hillcrest Syncline (Figure 5). Rocky Mountain to Blairmore strata were subdivided in a similar way into 5 domains.

The results of the statistical tests on the structural domains are summarized in Table 3. The acceptance or rejection of the null hypothesis, namely that all of the outcrops in the domain lie in a cylindrical fold, is indicated in Table 3 for the F-test and Chi-square test to a 95% level of confidence. These results show acceptance of the F-test and rejection of many of the Chi-square tests. The F-test allows for the larger, inter-outcrop, variations in orientation throughout the domain, whereas the Chi-squared test allows only for the smaller, intra-outcrop variations in orientation.

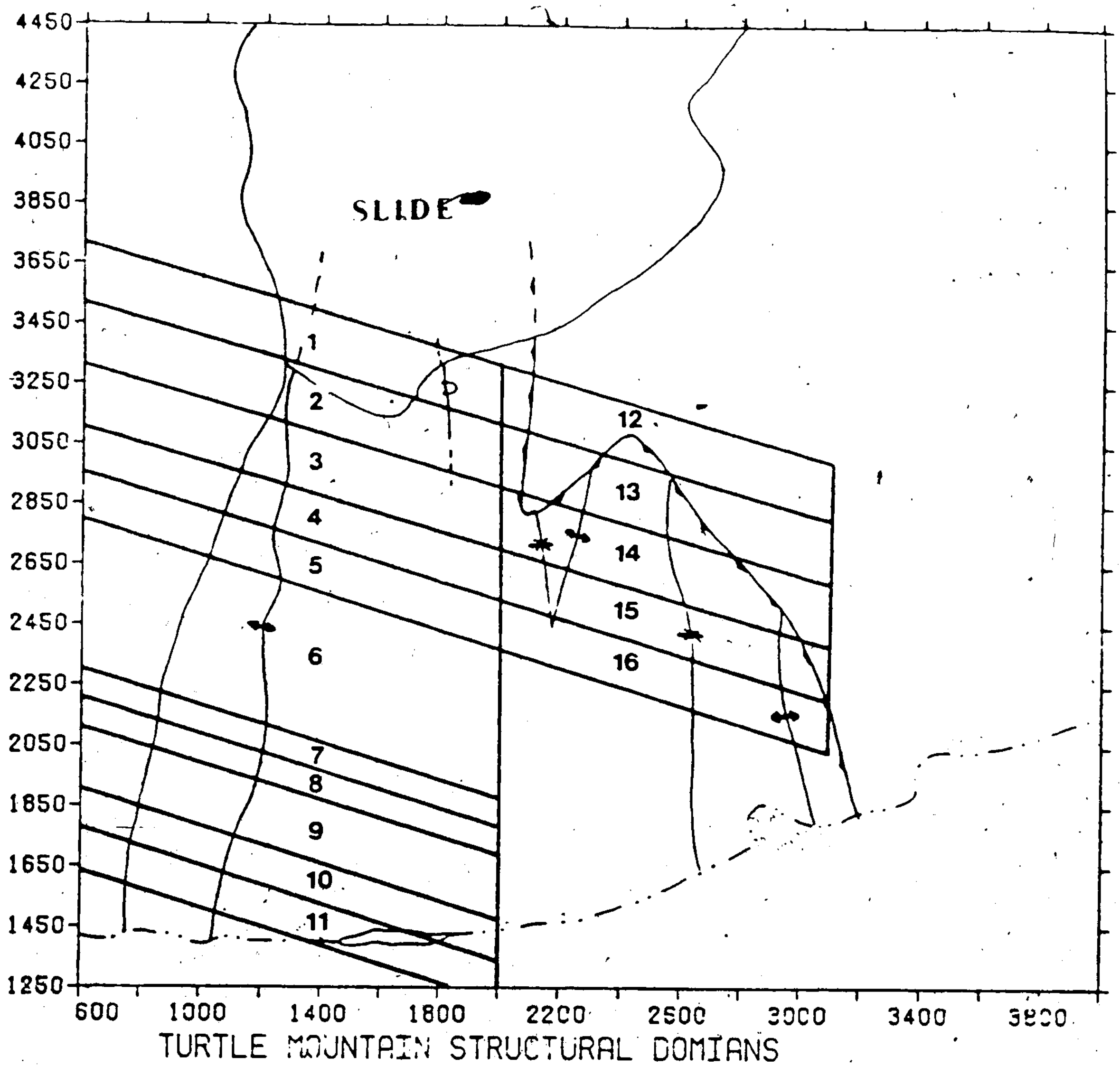


Figure 5. Structural Domains.

Domain	Fold T	Axis P	F-test	$F_{2,n-4}$ (.05)		Chi-squared	X_{n-2} (.05)		O/C #
1	196	8	0.13	3.18	A	33.9	25.0	R	17
2	201	1	5.22	3.21	R	56.0	62.8	A	48
3	196	4	0.77	2.59	A	203.2	64.0	R	49
4	203	6	1.71	3.44	A	280.0	36.4	R	26
5	199	7	0.65	3.68	A	166.0	27.6	R	19
6	194	9	5.04	2.93	R	180.0	31.4	R	22
7	201	5	6.74	6.94	A	15.7	12.6	R	8
8	202	8	2.53	4.10	A	224.0	21.0	R	14
9	204	17	5.16	6.39	A	124.6	12.6	R	8
10	190	12	0.92	3.63	A	117.0	28.9	R	20
11	185	17	1.73	3.59	A	101.0	30.2	R	21
12	187	21	0.25	5.79	A	76.4	14.1	R	9
13	183	17	0.74	4.26	A	21.9	19.7	R	13
14	194	20	0.27	3.18	A	56.1	25.0	R	17
15	183	20	2.71	3.52	A	185.0	32.7	R	23
16	180	11	6.28	19.0	A	7.2	9.5	A	6
Rundle Strata	196	7	14.9	3.0	R	1837.0	-	R	257
Cret. strata	181	19	1.38	3.1	A	627	119.0	R	98

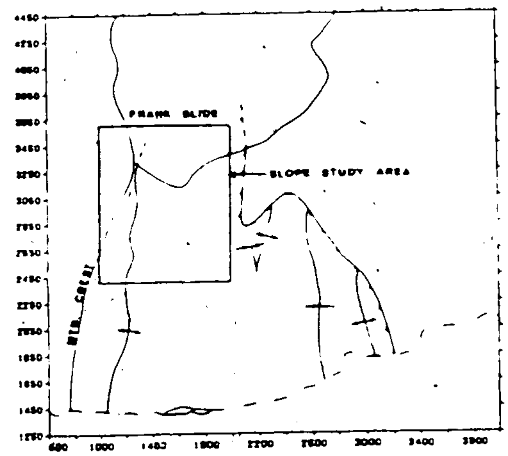
Table 3. Summary of statistics for structural domains.
O/C # = The number bedding orientations in the domain
n = The sample size (O/C #)
P = Plunge
T = Trend
A = Accept nul hypothesis
R = Reject nul hypothesis

Rejection can be attributed to the existence within domains of (1) incongruent minor folds, (2) fault or shear planes associated with mass-movement or (3) features produced by frost action. The acceptance of the F-test is the more important criterion for establishing cylindriclly folded domains as it takes into account larger scale variations in the orientation of a folded surface. For practical purposes the two areas that could not be subdivided into cylindrical domains were treated the same as the cylindrical domains.

Slope Stability Domains

The area of interest in the rock slope stability study (Figures 7 & 12) was divided into domains on the basis of the planarity of bedding. This criterion is different from that used to define the structural domains. For the purposes of this study the minimum area for a domain was 1000 m^2.

Domains were first established by inspection. Equal area pi-diagrams were produced for each domain and the eigenvalues calculated (Appendix 5). A large maximum eigenvalue and small and approximately equal imtermediate and minimum eigenvalues indicate a distribution about a mean orientation (Cheeney, 1983, p.121). The domain pi-diagrams of bedding normals and their eigenvalues were examined and the domains redefined by inspection until this pattern was recognized, see Appendix 5. The locations of the five planar domains established using this procedure are shown in Figure 6.



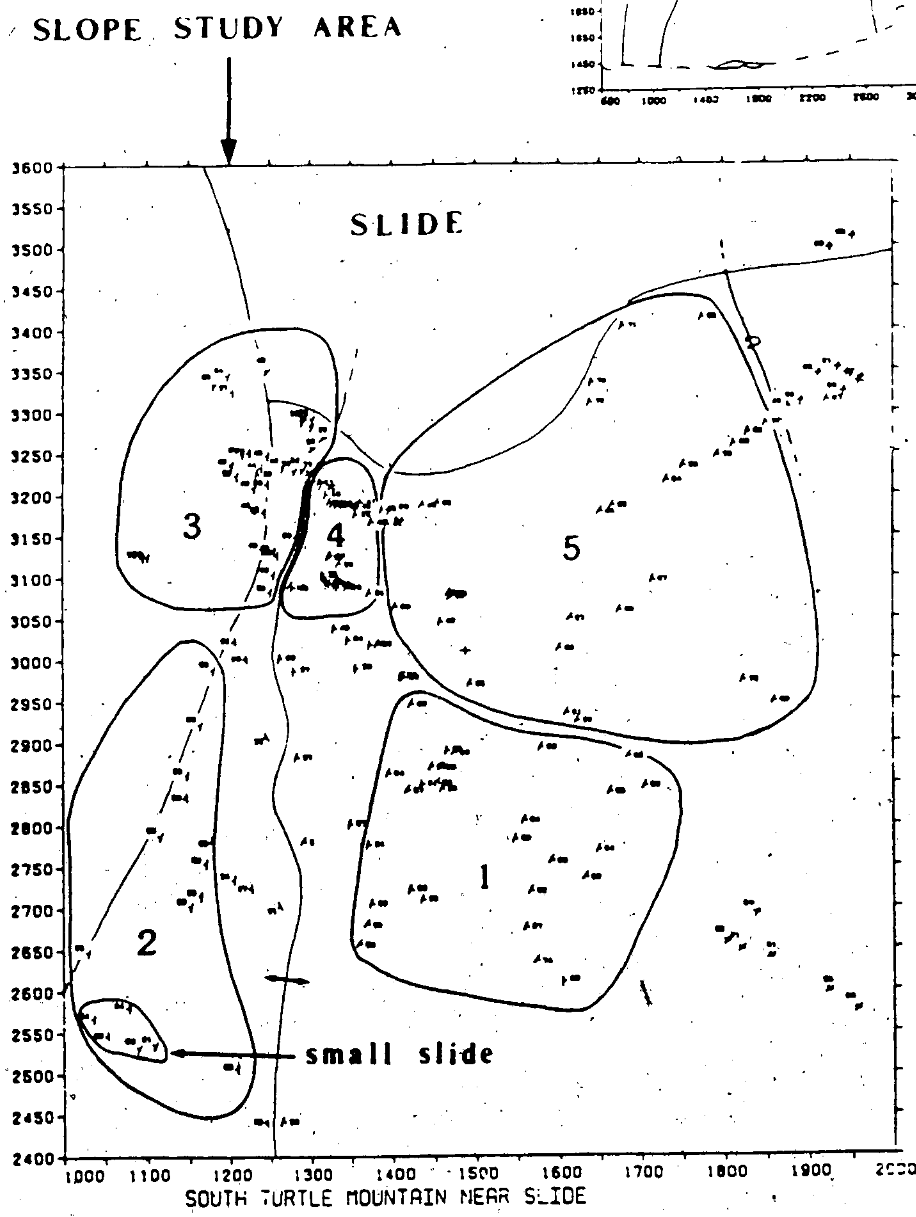


Figure 6. Slope Stability Domains.

B. Cross-sections

Three vertical structural cross-sections were drawn across the map, using the TRIPOD SECT command, as shown in Figures 8 to 10. Appendix 7 lists what lithologic units the symbols used in these cross-sections represent. The locations of the cross-sections were chosen to illustrate the relationships between fold geometry and mountain topography. The sections were drawn perpendicular to the trend of the Turtle Mountain Anticline. Outcrop data were projected down the fold axis for each domain onto a vertical section. Cross-sections rather than profiles were drawn because of the low plunge of the fold axis and the need to include topography. Projection distance was kept to a maximum of 200 m to reduce error in the projected positions of outcrops on the cross-section.

C. Maps

A base for the geological and slope stability maps was constructed using representative outcrops and the TRIPOD DRAW command. Topographic contours from the 1:5000 topographic map were traced onto both maps (Figures 11 & 12). Stratigraphic contacts were traced onto aerial photographs then transfered by hand to the maps.

5. Structure

A. Tectonic Setting

The study area is in the Southern Foothills of the Canadian Rocky Mountains foreland thrust and fold belt. Here the structure is characterized by west-dipping east-verging imbricate thrusts that in general developed from west to east from a basal zone of detachment.

B. Local Setting

The major structure in the map area is the Turtle Mountain Thrust. This can be traced 18 km north and at least 50 km south of the map area (Norris, 1955). For some of its length Mississippian carbonates are exposed in the hangingwall. This inlier of carbonate is resistant to erosion and forms the Turtle Mountain Range. The highest point in this range is Third Peak on Turtle Mountain in the map area. The oldest rocks exposed in the Turtle Mountain Range are from the Banff Formation and occur on Turtle Mountain 2 km north of the study area (Norris, 1955).

Strata in the hangingwall of the Turtle Mountain Thrust are folded by the north trending Turtle Mountain Anticline and Hillcrest Syncline which extend 7.2 km to the north and at least 10 km to the south of the map area (Norris, 1955). Erosion in the valley of the Crowsnest River north of Turtle Mountain has removed the syncline and the east limb of the anticline. South of the Crowsnest River, the east limb of the Turtle Mountain Anticline reappears 1900 m north of the map area on Turtle Mountain.

Paleozoic rocks crop out in the core of the Turtle Mountain Anticline. On Turtle Mountain this anticline is doubly plunging and folds the Mississippian strata tightly. The Hillcrest Syncline and Hillcrest Anticline reappear in the map area and continue to the south (Norris, 1955).

C. Major Structures

Turtle Mountain Thrust Fault

The Turtle Mountain Thrust Fault strikes N-S with a regional dip to the west and approximately 600 m of displacement (Norris, 1955). In the map area the Turtle Mountain Anticline and the Hillcrest Syncline appear to end downward against the Turtle Mountain Thrust. However, between the axial planes of these folds in the footwall the thrust is approximately horizontal. Thus in the map area the fault is divisible into two segments; (1) a west dipping western segment beneath the west limb of the Turtle Mountain Anticline, (2) a horizontal segment beneath the east limb of the Turtle Mountain Anticline and the Hillcrest Syncline. The relationship between the fault and bedding in the hangingwall is as follows. The western segment appears to coincide with a hangingwall flat in the Banff Formation and the eastern segment with a hangingwall ramp from the Banff to the Blairmore Group. The angle between bedding in the hangingwall ramp and the fault is approximately 90^{o}, possibly the result of rotation during movement along the fault. The thrust follows the framework of thinned skinned tectonic deformation like other faults in the Rocky Mountain Foothills with only slight modifications such as the high angle between bedding in the hangingwall and the thrust fault.

Immediately above the horizontal segment of the Turtle Mountain Thrust is a recumbent fold with a gentle interlimb angle of about 130°. The fold axis trends at 200°. This fold may be the result of fault drag.

Turtle Mountain Anticline

The Turtle Mountain Anticline is a symmetrical non-cylindrical planar fold with an interlimb angle of about 50°. The fold axis trends about 190° and plunges between 0° and 20° (Table 3). The axial surface has an approximate dip-direction and dip of 290° and 90° near the slide. This orientation was calculated using the fold axis and the trace of the axial plane on a profile. Axial plane cleavage with an orientation of 285° 90° was observed at one location near the Turtle Mountain axial trace (see Figure 10). The anticline is a flexural slip fold as slickensides can be observed on bedding surfaces (Krahn, 1974).

Hillcrest Syncline

The Hillcrest Syncline in the hangingwall of the Turtle Mountain Thrust folds the Mesozoic strata (Figure 10). The orientation of the axial plane and fold axis are approximately 270° 70° and 180° 20°, respectively. This is an asymmetrical, upright fold.

Hillcrest Anticline

The Hillcrest Anticline starts in the map area and parallels the Turtle Mountain Thrust to the south for at least 10 km. This anticline has as apical angle of 80° and an axial plane with a dip direction and dip of 272° 75°, respectively.

D. Minor Structures

Bedding

In the study area bedding is folded on a macroscopic scale. On the limbs of the folds, however, at a scale of around 1000 m^2, bedding can be considered penetrative as the pi-diagrams of the slope stability domains show (Appendix 5). The bedding surfaces show evidence of flexural slip as a result of folding.

Normal Faults

Small-scale normal faults are present in strata close to the axial surface of the Turtle Mountain Anticline and were also observed in the Kootenay Group adjacent to the main coal seam (Figure 10).

Minor Folds

West of the Hillcrest Syncline a small anticline causes the Kootenay strata to dip west (Figure 10). Due to the poor outcrop in the area orientations of the axial plane and fold axis were unobtainable.

Joints

Joint data on Turtle Mountain were gathered in both Paleozoic and Mesozoic strata. Mesozoic outcrops are scarce and small and the joints in them are widely spaced; as a result, the number of joints in Mesozoic rock for which orientations were available was insufficient to warrant analysis. Joints in the Paleozoic strata are numerous. Joint spacing ranges from 2 cm to 2 m and is controlled by bedding thickness and competency. In general the more competent the rock and thinner the bedding the more closely spaced the joints. Joints generally end against bedding planes. The largest joints were seen in the area of the small slide (Figure 10) and are about 8 m^2.

The computer program ORIENT was used to process the joint orientations in the slope stability domains and draw the pi-diagrams in Appendix 6. Joint measurements taken by P. McLellan in 1982 on Turtle Mountain were included in this study.

Although the orientation of joints varies widely, inspection of the pi-diagrams (Appendix 6) suggests that a broad girdle of joint normals may be present in each domain. Statistical tests described in Mardia (1972, p. 275-278) were carried out to determine if the joints were randomly distributed or formed a girdle distribution. These tests are based on a Bingham distribution (Mardia, 1972). The null hypothesis of a random distribution of joints was rejected, at a 95% confidence limit in all domains (Table 4). The null hypothesis of a girdle pattern was accepted in all domains at a 95% level of confidence (Table 4). While the girdle pattern of joint normals is present, inspection

Domain Number	Sample size (n)	Random dist. X^2 test		Girdle dist X^2 Test	
1	42	13.80	R	2.88	A
2	44	20.20	R	4.06	A
3	139	33.42	R	3.31	A
4	52	19.90	R	3.03	A
5	43	25.78	R	5.98	A

Table 4 Statistics on random and girdle distributions of joint data. $X_5^2 = 11.07$ for the random distribution and for the girdle distribution $X_2^2 = 5.99$.

X^2 = Chi-squared test(.05).

R = Rejected

A = Accepted

dist. = distribution

of the minimum eigenvectors for all of the domains does not show any common grouping. This means that there is little correlation of the girdle patterns between the domains.

To compare the jointing in different domains, bedding in each domain was rotated to the horizontal using the program ORIENT. Appendix 6 shows the rotated pi-diagrams of the joint normals for the slope stability domains. While most of the joint normals in these diagrams lie close to the primitive circle a number do not, indicating that some joints developed at an oblique angle to bedding. This is not usually the case for joints in sedimentary rocks. A summary of jointing on the Turtle Mountain Anticline (Figure 12) shows some of the oblique joints. These oblique joints might be have been caused if rock in certain areas acted anisotropically to the stress that caused the joints to form.

In a fold, joints can be classified with respect to their relationship to fold geometry (Price, 1966). With respect to the Turtle Mountain Anticline, ac joints are present in domains 1, 4 and 5 on the east limb and bc joints in domains 2 and 3 on the west limb. Shear joints develop about 30^{o} from the ac joints and can be recognized in domains 3 and 5.

In addition to the above joint sets each pi-diagram shows a number of other joint sets to be present. The best development of ac, bc and shear joint pattern occurs in rocks that have little variation in competency between strata at the time of joint formation (Price, 1966). The Mississippian rocks in the map area vary considerably in competency and this could explain the development of these additional joints. Variation in stress direction due to the movement of the hangingwall rocks over a ramp might also cause the formation of joints which can not be related to fold geometry or regional stress direction. Unloading of the rocks would also produce some joints with different orientations. Most of the joints present can be related to the fold geometry and regional stress direction. Other joints due to unloading, changes in stress direction and variation in competency of the rock are also present.

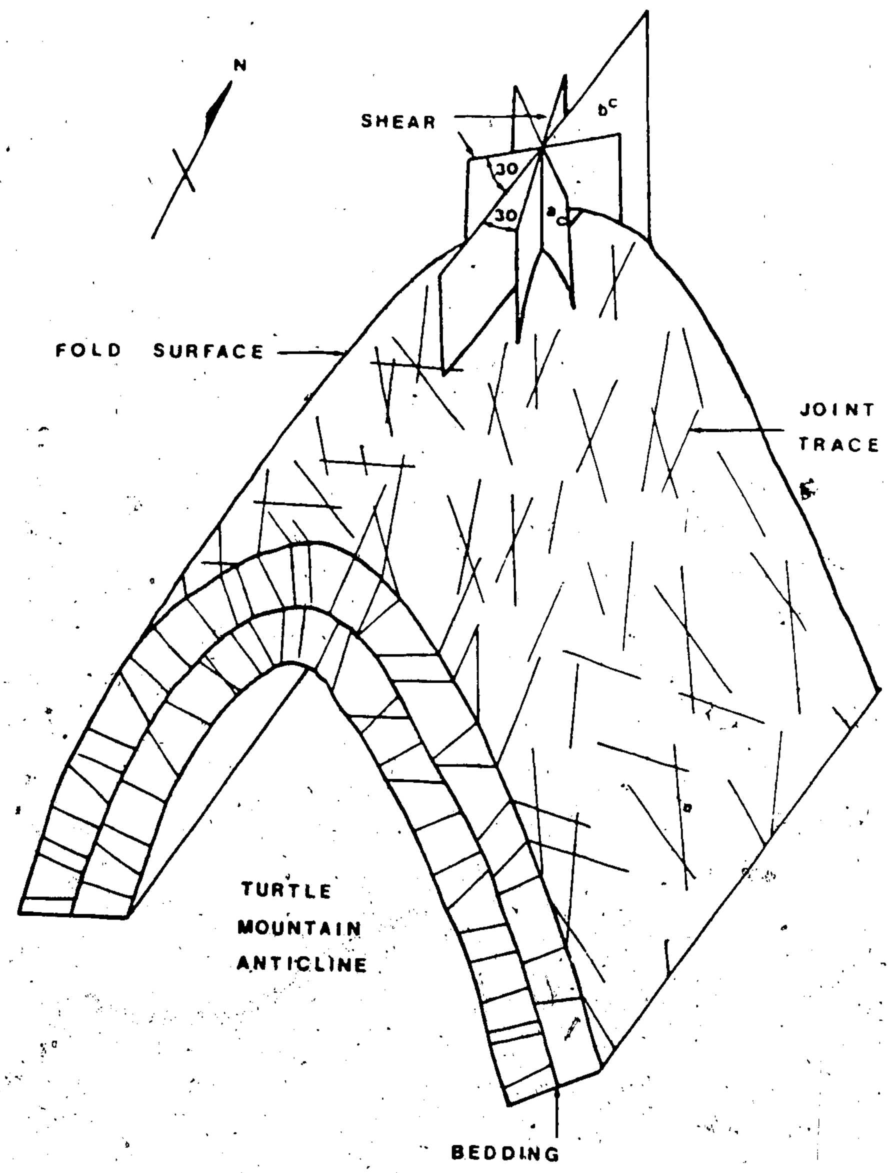


Figure 12. Summary diagram of Joint Orientations on Turtle Mountain.. Point of View = 315° 30°

6. Slope Stability Study

A. Introduction

The Frank Slide is a classic example of the mass movement of rock. The slide was originally described as occurring along joint planes perpendicular to bedding in a west dipping monocline (McConnell and Brock, 1904). Later geological mapping (Leach, 1904; MacKenzie, 1913) showed an anticline with an axial plane close to the crest of Turtle Mountain. The rupture surface was then reinterpreted as occurring along bedding plane flexural slip surfaces on the east limb of the anticline (Cruden and Krahn, 1975). This study is a reconnaissance survey of South Turtle Mountain looking at the modes of movement that have occurred and areas of possible instability.

The three basic types of rock slope movement are toppling, plane sliding and wedge sliding (Goodman, 1980, p. 256). All three types of movement can be observed on Turtle Mountain. Wedge sliding occurs when two planes define a tetrahedral block where the inclination of the line of intersection daylights on the slope (Plate 1b). Toppling occurs when the weight vector of a discrete body of rock passes outside the base of the block and the block rotates outward, cracks form behind the block (Plate 1a). Plane sliding is comparatively rare in rock slopes (Hoek and Bray, 1981) and occurs when an inclined plane of weakness has a shallower dip than the slope and a steeper dip than the angle of internal friction of the rock.

The area of interest in the rock slope stability study (Figures 7 & 12) was divided into domains. These domains are volumes of rock which possess a statistical homogeneity with respect to one or more geological structures. The structure used to define the domains is bedding (Figure 6).

When multiple sets of discontinuities intersect at oblique angles, kinematic studies may be helpful in predicting the most likely pattern of slope failure. A kinematic study is most easily carried out on stereographic projections (Hoek and Bray, 1981).

Limit equilibrium analysis looks at the equilibrium conditions at failure between the driving and resisting forces to determine if a rock mass is stable. This type of study requires knowledge of the strength characteristics of the rock mass. The characteristics of the rock mass on Turtle Mountain were obtained from shear tests run on the rock in a previous study (Krahn, 1974). Back analysis of slope failure is useful to determine the shear strength of the rock mass. Detailed knowledge of the groundwater conditions and rock mass fabric is necessary to use this technique. In a previous study (Cruden and Krahn, 1978), a back analysis of the Frank Slide was done to obtain the angle of friction of discontinuities within the slope for a factor of safety of 1.

Rock slope failure is caused by the driving forces exerted on the rock mass by gravity, pore pressure, frost action and transient events such as earthquakes. The mountain slope can be treated as fully drained in this study due to the steepness of the slope and the numerous joints which provide good permeability in the rock mass. This allows us to neglect the effects of pore pressure and frost action. Turtle Mountain is in a seismically inactive area as shown by an seismic activity map (Kanasewich and McCloughan, 1984), so the effect of earthquakes on the slope is also neglected. A possible transient event that might affect the slope is closure of the Frank Mine workings at the base of Turtle Mountain. The amount of closure of the mine workings is unknown. The effect of any mine closure on the cohesion of the individual particles on the slope above is also unknown. This leaves the effect of gravity on the rock mass as the only driving force considered in the limit equilibrium study. The resisting force considered is the force of friction along the different discontinuities in the rock mass and the orientation of these discontinuities with respect to the topographic slope.

B. Fabric Elements

Failure due to the effect of gravity on a hard rock mass is possible only if discontinuities exist in the rock which permit the movement of discrete blocks (Goodman, 1980, p. 255). A rock mass has fabric if it contains penetrative planes or lines known as fabric elements. The main fabric elements in the rock mass in this study are bedding, joints and faults. These fabric elements form the discontinuities in the rock mass that define discrete blocks. The few fissures present in the study area (Figure 11) are major discontinuities.

Bedding planes are major discontinuities providing the most likely rupture surface on the east limb of the Turtle Mountain Anticline. Joints at oblique angles to each other make wedge failure possible on the west limb of the anticline. Also on the west limb, bedding provides the discontinuity along which tension cracks associated with toppling can form. Plane sliding along bedding is possible on the east limb where jointing and fissures could provide the removal of the lateral restraint for a block. Discontinuities at the toe of the slope along which outward movement of the rock could occur are axial plane cleavage near the axial plane of the recumbent fold and the Turtle Mountain Thrust Fault.

C. Toppling Failure

Examples of toppling can be found on the west limb of the Turtle Mountain Anticline east of the mountain crest (Plate 1a; Figure 11). Plate 1a depicts a possible toppling situation with tension cracks developing along bedding. Evidence of toppling failure exists in local areas of high slope angle over both the Frank Slide and the Small Slide (Figure 11). Figure 13 shows a cross-section through the Small Slide and the stereographic projection concerned with the kinematics of toppling in the area. The cross-section

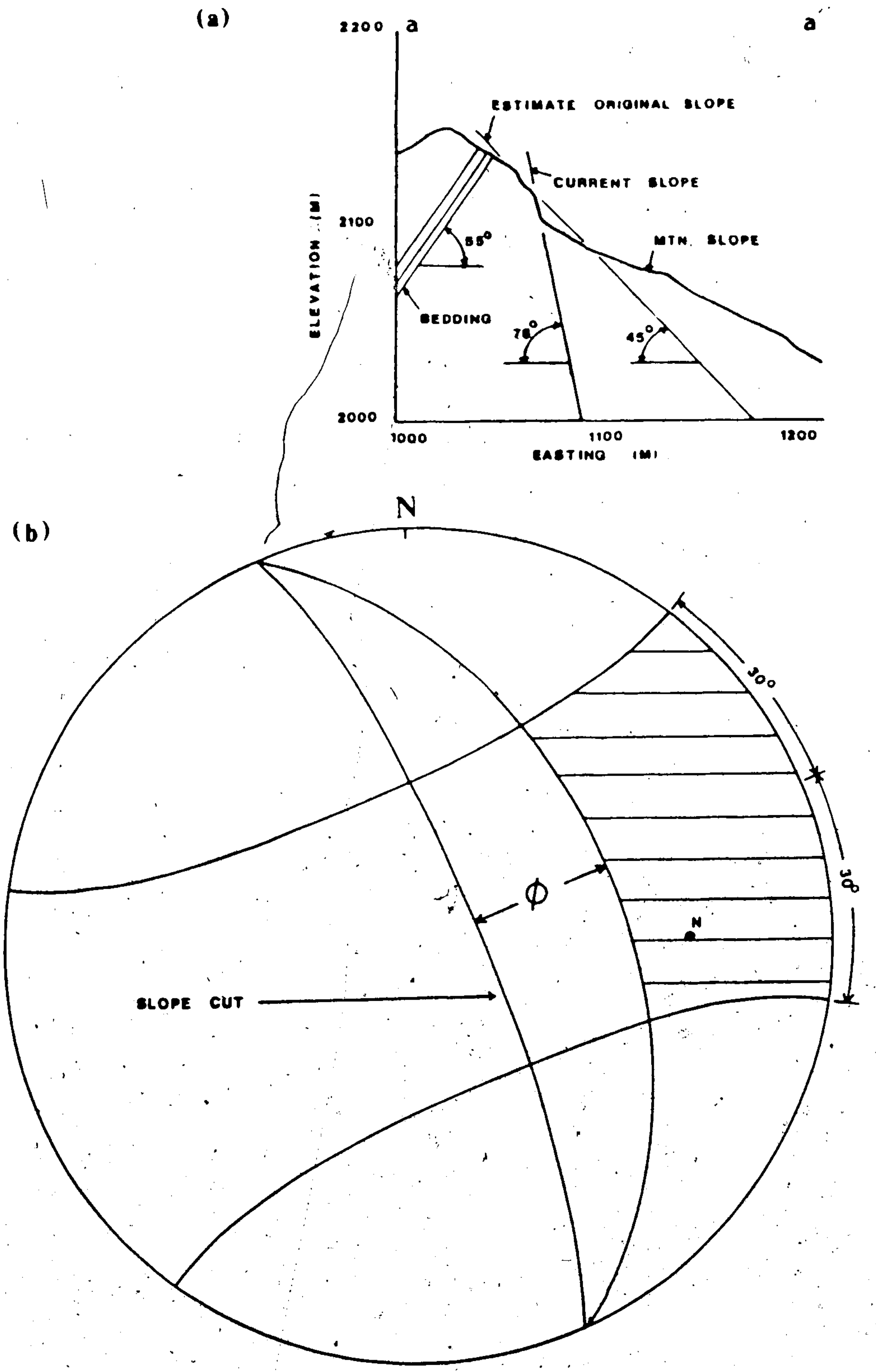


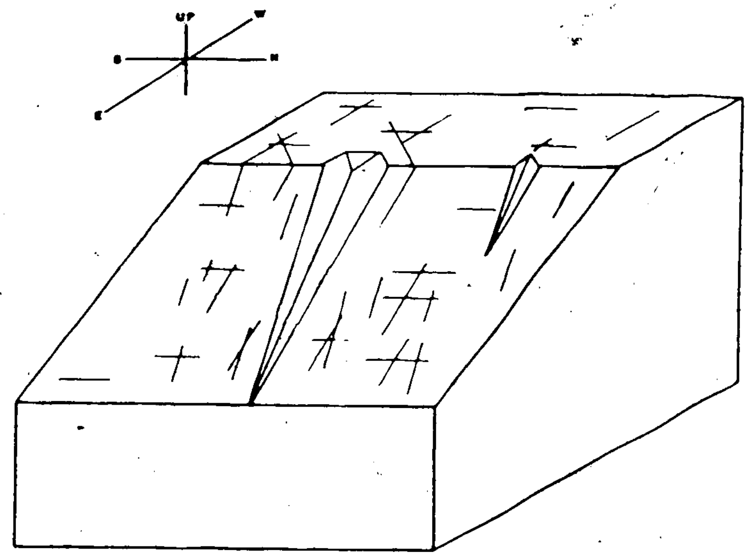
Figure 13. Toppling Failure Small Slide. a) cross-section Small Slide b) Stereonet Diagram. For symbols see text.

shows that the rupture surface is bedding whose pole is represented on the stereonet by N. If the peak angle of friction , , for the bedding flexural slip surface is 28° (Cruden and Krahn, 1978), toppling is kinematically possible because the normal to bedding (N) falls in the ruled area where toppling failure is possible (Goodman, 1980, p. 265). In the area of the Small Slide, toppling failure has occurred where the lateral restraints on a block of rock have been removed by either erosion or previous failures. The volume of rock above the small slide that could fail by toppling is 44,000 m^3. In domain 2 outside the local area of the small slide and in domain 3 the topographic slope is gentler and toppling failure cannot occur as the weight vector of a block would not pass outside the base of the block.

D. Wedge Failure

The results of wedge failure were observed in the local area of the Small Slide on the west limb of the Turtle Mountain Anticline shown in Plate 1b. Figure 14a is an isometric block diagram of jointing in the area and typical wedge failures while Figure 14b shows the stereographic projection depicting the kinematic possibility of wedge failure. The estimated original slope has a slighty different strike from the present slope where the potential toppling situation is located (Figures 14b & 15b). In this figure only the joint normals (N) relative to the kinematic analysis for wedge failure in the area of the

(a)



(b)

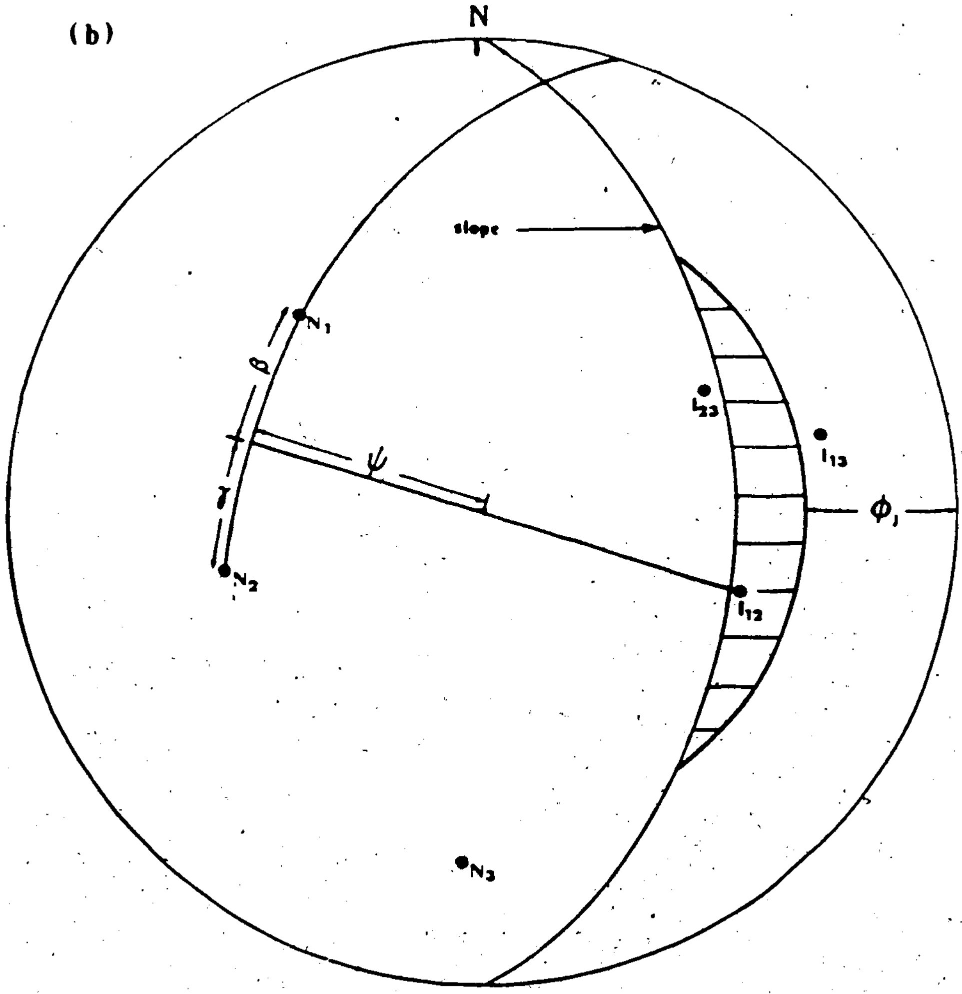


Figure 14. Wedge Failure Small Slide. a) block diagram
b) stereonet diagram.
For symbols see text.

Small Slide are shown for clarity. These joint orientations are a subset of the joint fabric in slope stability domain 2 (Appendix 6).

In Figure 14 the intersection (I_{12}) of joint planes 1 and 2 falls in the ruled region which represents the area of kinematically possible wedge failures (Cruden, 1984). The plunge of I_{12} is less than the estimate of the original slope dip of 45° (Figure 14) and greater than the peak angle of friction (ϕ_j) for joint surfaces of 32° obtained from shear testing (Cruden and Krahn ,1975). The factor of safety was calculated for wedge failure using a method described in Cruden (1984, p. 679). The angle ψ is the inclination of the plane containing N_1 N_2 to vertical. The angles α and β on the plane perpendicular to I_{12} are the angles between the reactions to the weight of the wedge acting normally to joint planes 1 and 2. For the Small Slide $\psi=42^{\circ}$, $\alpha=21^{\circ}$, $\beta=22^{\circ}$ and $\phi_j=32^{\circ}$. The factor of safety for these values is 0.75, indicating probable failure. If a factor of safety of 1 is assumed for the slope by back analysis, an angle of friction of 40° is obtained for the Small Slide area. The maximum volume of rock involved in further failure above the small slide to the mountain crest is again estimated at 44,000 m^3. Elsewhere on the slope the gentler angle of the slope makes wedge failure not possible as none of the joint intersections falls in the area that indicates failure is kinematically possible.

E. Plane Failure

The east limb of the Turtle Mountain Anticline adjacent to the Frank Slide was looked at to see if plane failure was possible. The area of interest was between gully A adjacent to the Frank Slide and gully B to the south (Plate 2). A two dimensional analysis of this area is reasonable due to the removal of the lateral restraints by erosion in the two flanking gullies. The area along cross-section c-c' was studied to determine if failure along bedding planes is possible. The average dip of bedding is 55° East while the average slope dip is 35° East. For plane failure to occur, bedding must daylight on the slope. On the scale of the cross-section bedding does not daylight, so the slope is kinematically stable with respect to failure along bedding. This is also the case with domains 1, 4 and 5.

A second study was done on a smaller area closer to the axial plane of the Turtle Mountain Anticline where the dip of bedding is shallower and daylights on the slope. Figure 15 displays the cross-section b-b' (from Figure 11) and the stereographic projection concerned with plane failure. An estimate of the amount of rock that would be involved in a plane failure here is 320,000 m^3. This estimate is for the area bound by gully A (Plate 2), the axial trace of the Turtle mountain Anticline, the adjacent ridge to the south of gully A and the point where the bedding daylights on the slope. Axial plane cleavage and

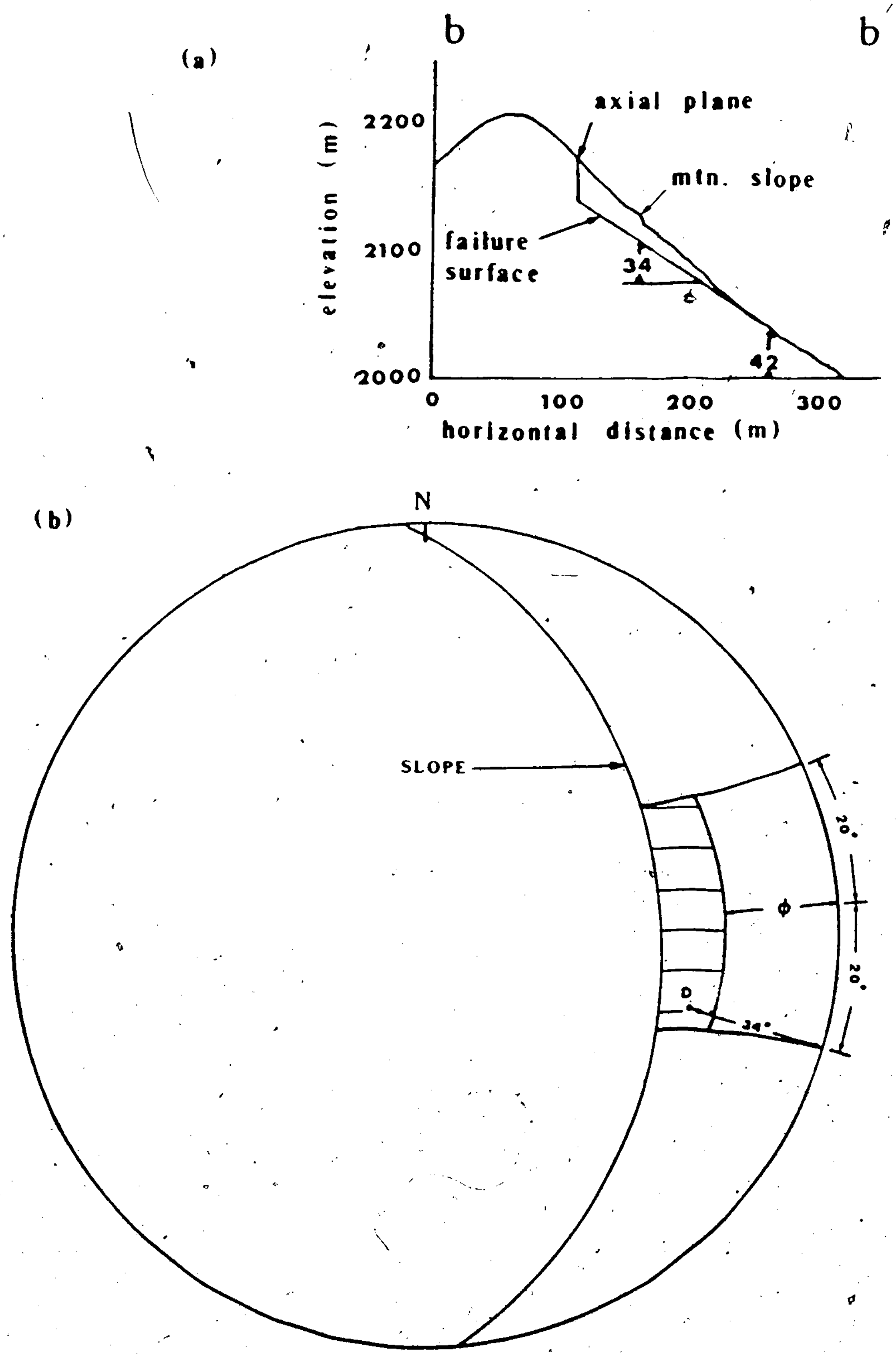


Figure 15. Plane Failure. a) cross-section b) stereonet
For symbols see text.

small faults present near the axial plane were observed to the south (Figure 10) and indicate the possibility of a discontinuity coinciding with the axial plane. This could provide a rupture surface for slope failure near the Turtle Mountain Anticline axial plane. On the stereographic projection the dip vector of bedding (D) is in the striped area which represents the area where plane failure is kinematically possible (Hoek and Bray, 1981). Shear tests on the flexural slip surfaces gave an angle of friction, ϕ, of 28° (Cruden and Krahn, 1975). The average slope angle of 42° was obtained from cross-section b-b' (Figure 15a). While the two dimensional analysis shows that kinematically this area can fail, lateral suport of the block has not been taken into account by the study and there is some lateral support to the south. If failure did occur, toppling and wedge failure of the rock to the west of the axial plane would be possible due to the increase in the slope.

F. Circular Failure

Until now, only rock slope failure controlled by discontinuities in the rock mass such as bedding and jointing have been discussed. Circular failure occurs when conditions arise where the individual particles of the rock mass are very small compared with the size of the slope and when these particles are not interlocked as a result of their shape (Hoek and Bray, 1981).

The shape of the failure surface for the Frank Slide approximated a circular failure curve (Cruden and Krahn, 1978, Figures 6 to 9). Movement of the slide out along a horizontal plane at the toe and the toppling and wedge failure west of the Turtle Mountain Anticline Axial Plane gave the slide rupture surface this shape.

The high amount of jointing on the slope between gullies A and B causes the individual particles of the rock mass to be interlocked and small when compared to the size of the slope. To use the circular failure method of analysis (Figure 16) along cross-section c-c' (Figure 11) it is necessary to show that the individual particles of the rock mass can become unlocked. For a slope of 35º and a factor of safety of 1, Figure 17 shows the value of cohesion which is mobilized at failure (Hoek and Bray, 1981, p. 234) and that water in the slope adversely affects stability. If flexural slip surfaces exist parallel to the rupture surface, factors of safety are less than in a dry slope. Water pressure may accumulate in cracks in the rock and trigger movements that will destroy the cohesion of the rock mass. Seasonal freezing of the east face of Turtle Mountain would form an ice dam which could hinder drainage of the slope and allow water pressure to build in cracks. Other factors that can destroy the cohesion of the rock mass on Turtle Mountain are limestone solution along bedding planes and movements associated with closure of the Frank Mine. In the long term cohesion cannot be relied on to maintain the stability of the slope. For the above

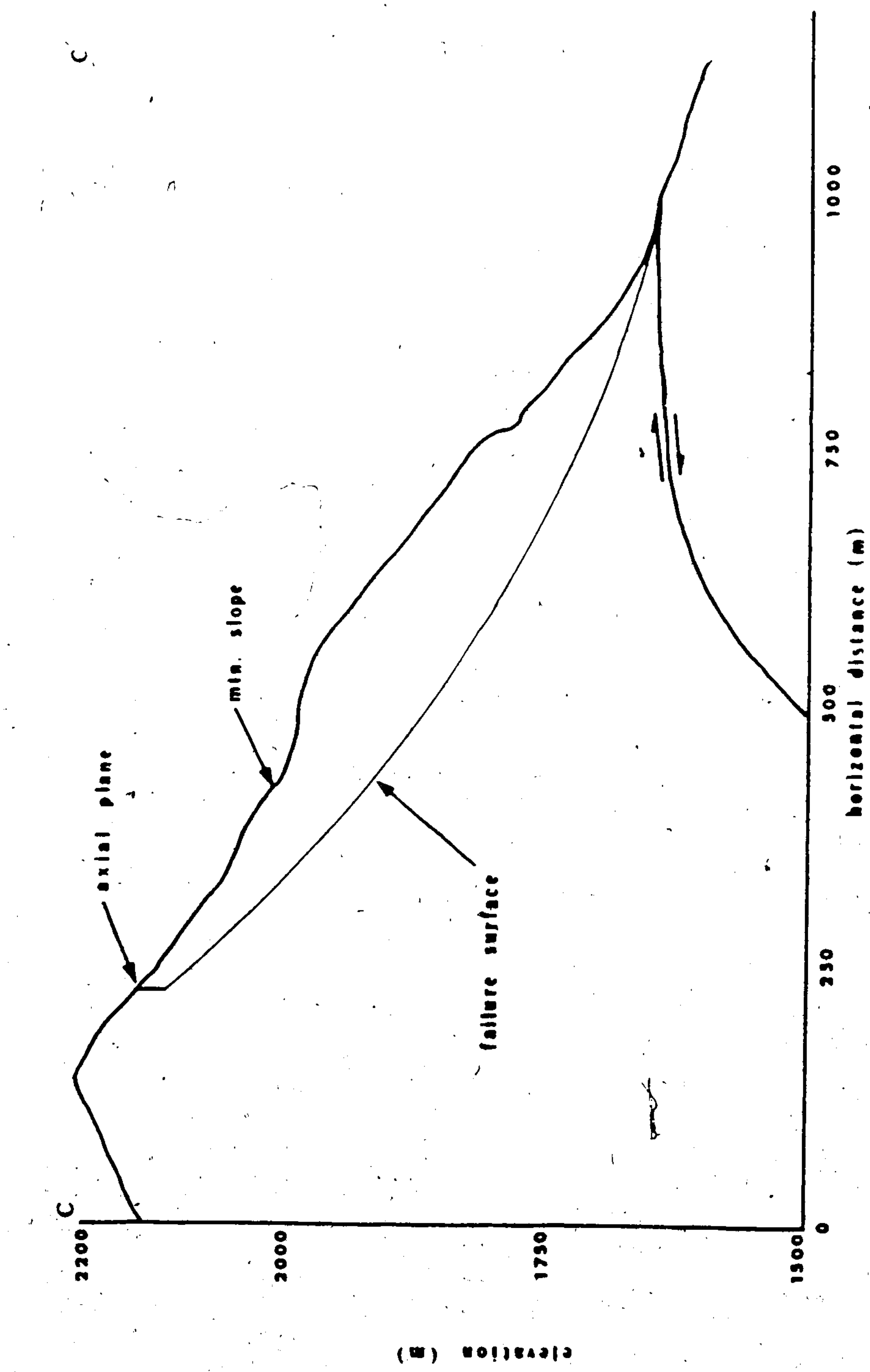


Figure 16. Circular Failure.

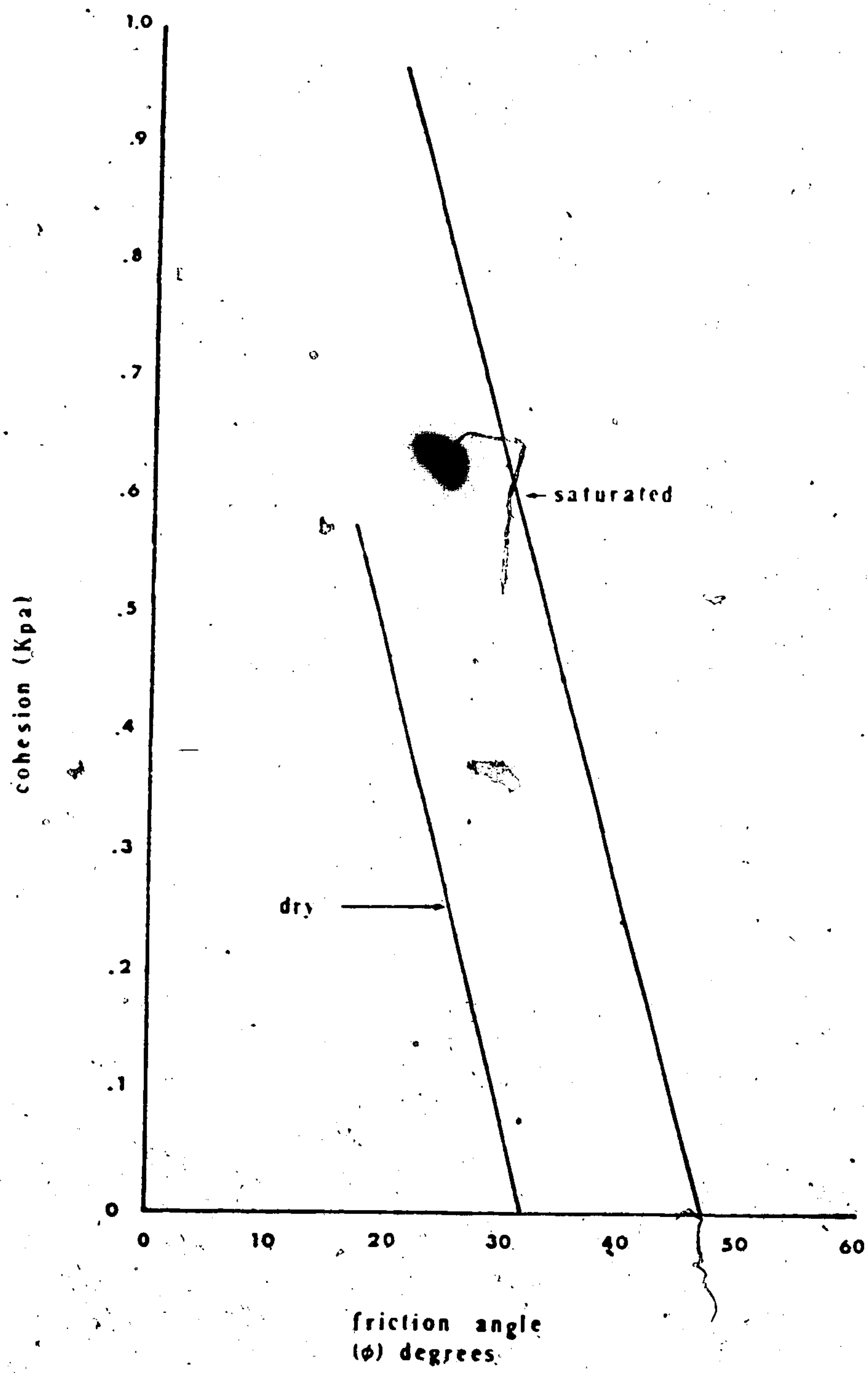


Figure 17. Values of cohesion. With a factor of safety of 1 and different values of friction angle for a slope of 35°.

reasons I feel that the circular failure analysis gives a reasonable representation of the slope stability when all the factors involved are considered.

Erosion in gullies A and B (plate 2) again makes the two-dimensional analysis (Figure 16) representative of the three-dimensional situation. From the cross-section (Figure 16) and the area between gullies A and B the maximum volume of rock that could be involved in circular failure here has been calculated as 18,500,000 m^3. The slope was treated as fully drained and the angle of friction used was 37.2° with a cohesion of zero (Cruden and Krahn, 1975). Using the circular failure chart in Hoek and Bray (1981, p. 343) a factor of safety of 1.1 was obtained for the slope. This low value indicates that the possibility of circular failure of this area must be considered.

7. Conclusions and Recommendations

Detailed mapping and the use of computer based mapping techniques have better defined the structure of South Turtle Mountain. The Turtle Mountain Fault is a hangingwall flat in the Banff Formation beneath the west limb of the Turtle Mountain Anticline. The thrust cuts up section from the Banff to the Blairmore and is approximately horizontal beneath the Hillcrest Syncline and the east limb of the Turtle Mountain Anticline. All folds in the hangingwall of the Turtle Mountain Fault end downward against the fault. The Turtle Mountain Anticline is a symmetrical, non-cylindrical, upright plunging fold with an interlimb angle of 55^{o} and a fold axis trending 190^{o} and plunging from 1^{o} to 20^{o}. The Hillcrest Syncline is an asymmetrical, non-cylindrical inclined fold with an interlimb angle of 70^{o} and a fold axis that trends and plunges at 180^{o} and 20^{o}, respectively. A recumbent fold in the Paleozoic strata above the Turtle Mountain Thrust Fault, adjacent to the Frank Slide may be the result of fault drag.

In the area chosen for slope stability analysis five domains were established on the basis of bedding planarity. A broad girdle pattern of the joint normals is present in each domain. Once the bedding in each domain was rotated to the horizontal the girdle patterns in the different domains were compared and no relationship between them could be found. A relationship between the geometry of the Turtle Mountain Anticline and the joints was recognized with ac, bc, and shear joints present in different domains. While these joints are present in the domains many other joints are also present which cannot be related to the fold or the regional maximum principal stress direction in the area. This shows that the joints likely formed at different times, some related to the folding and other to processes such as unloading, movement over the Turtle Mountain Fault and changes in the stress direction.

In the domains defined for the slope stability study toppling, wedge sliding and plane sliding are not kinematically possible. In local areas within these domains, however, where the slope is steeper than normal, toppling, wedge sliding and plane sliding are kinematically possible. Analysis of wedge failure on intersecting joint surfaces in the Small Slide gave an angle of internal friction of 40^{o}. Plane failure along bedding planes adjacent to the Frank Slide and below the axial trace of the Turtle Mountain Anticline proved to be kinematically possible for a two dimensional analysis. In the three dimensional situation lateral support to the south would likely stabilize this block. The volume of rock involved in failure in these localized area is not enough to be concerned about on the large scale in which we are most interested.

Based on the assumption that in the long term cohrsion cannot be relied on to maintain the stability of the slope, a circular failure analysis of the area between gully A and B was carried out. The cohesion of the joint bound individual particles of the rock slope might be destroyed by; (1) closure of the Frank Mine, (2) limestone solution along bedding planes or (3) the increase of pore pressure in the cracks in the rock mass. A factor of safety of 1.1 was obtained for this analysis which means that the possibility of circular failure can not be ruled out.

Based on the determination of the structure in the map area and the results of the slope stability analysis the following recommendations for further work are made.

1. Establish further slope movement monitoring stations on the slope adjacent to the Frank Slide below the axial trace of the Turtle Mountain Anticline (see Figure 11). These new stations would detect any slope movement in the region below the axial plane of the Turtle Mountain Anticline.
2. Establish further slope movement monitoring stations on the slope adjacent to the Frank Slide above the Turtle Mountain thrust (see Figure 11). These new stations would detect any outward movement of the slope along discontinuities such as the surface of the Turtle Mountain Fault or horizontal joints in the area of the axial plane of the recumbent fold.
3. Monitoring points should be established on the walls of the Frank Mine subsidence pits (Plate 2) to try and determine if the mine is undergoing closure.

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(a)

(b)

Plate 1. Potential Failure a)toppling b) wedge

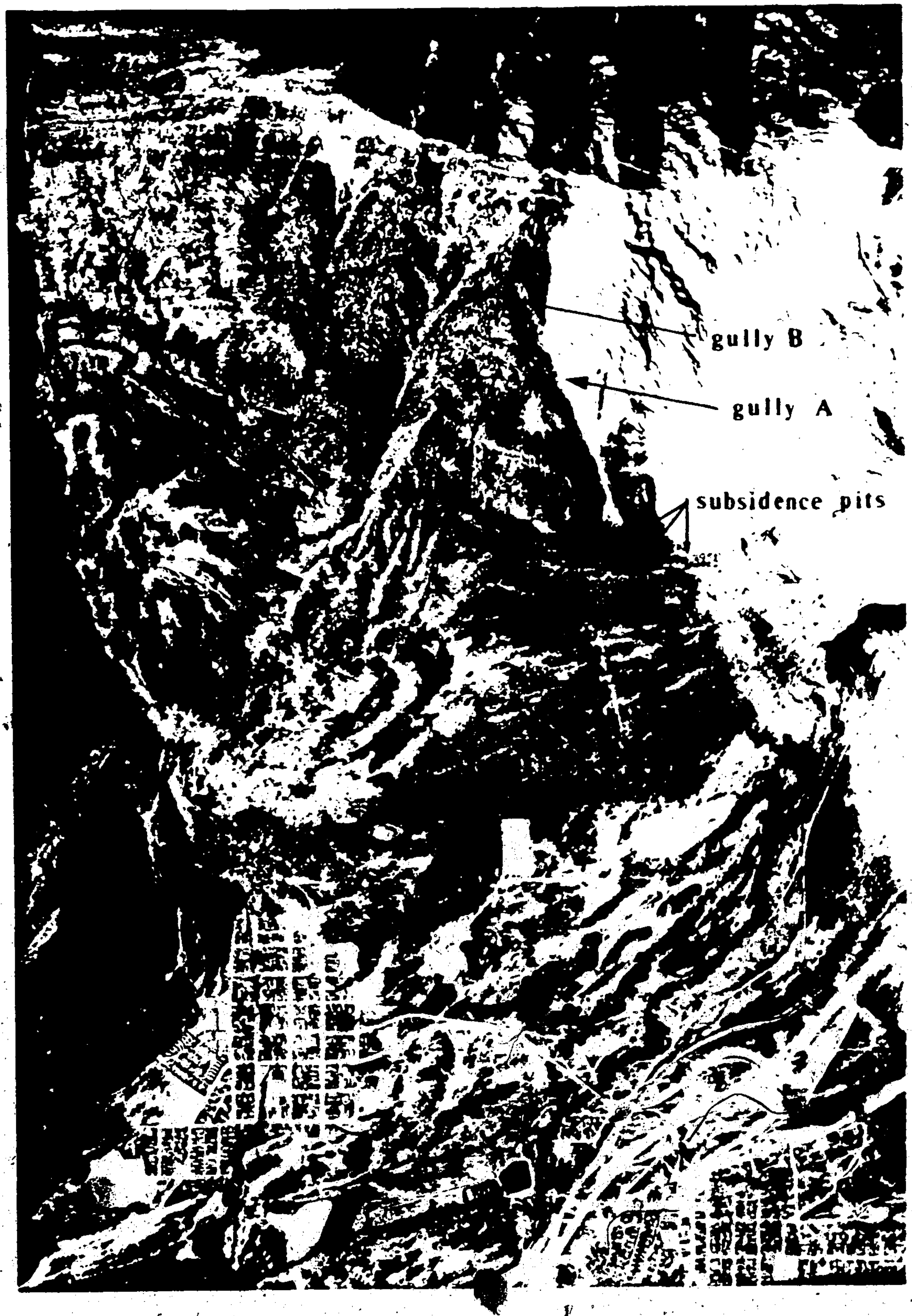


Plate 2. Airphoto Turtle Mountain. (A=gully A, B=gully B).

9. Appendices

A. Appendix 1

Lithologic Section

Legend

Lithology

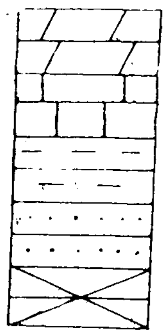
Dolomite

Limestone

Shale

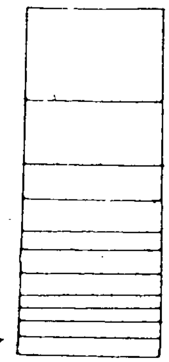
Siltstone

Covered Interval



Bedding Thickness

Massive	>2.0m	
Thick	0.6m	- 0.2m
Medium	0.2m	- 0.6m
Thin	60mm	- 0.2m
Very Thin	<60mm	

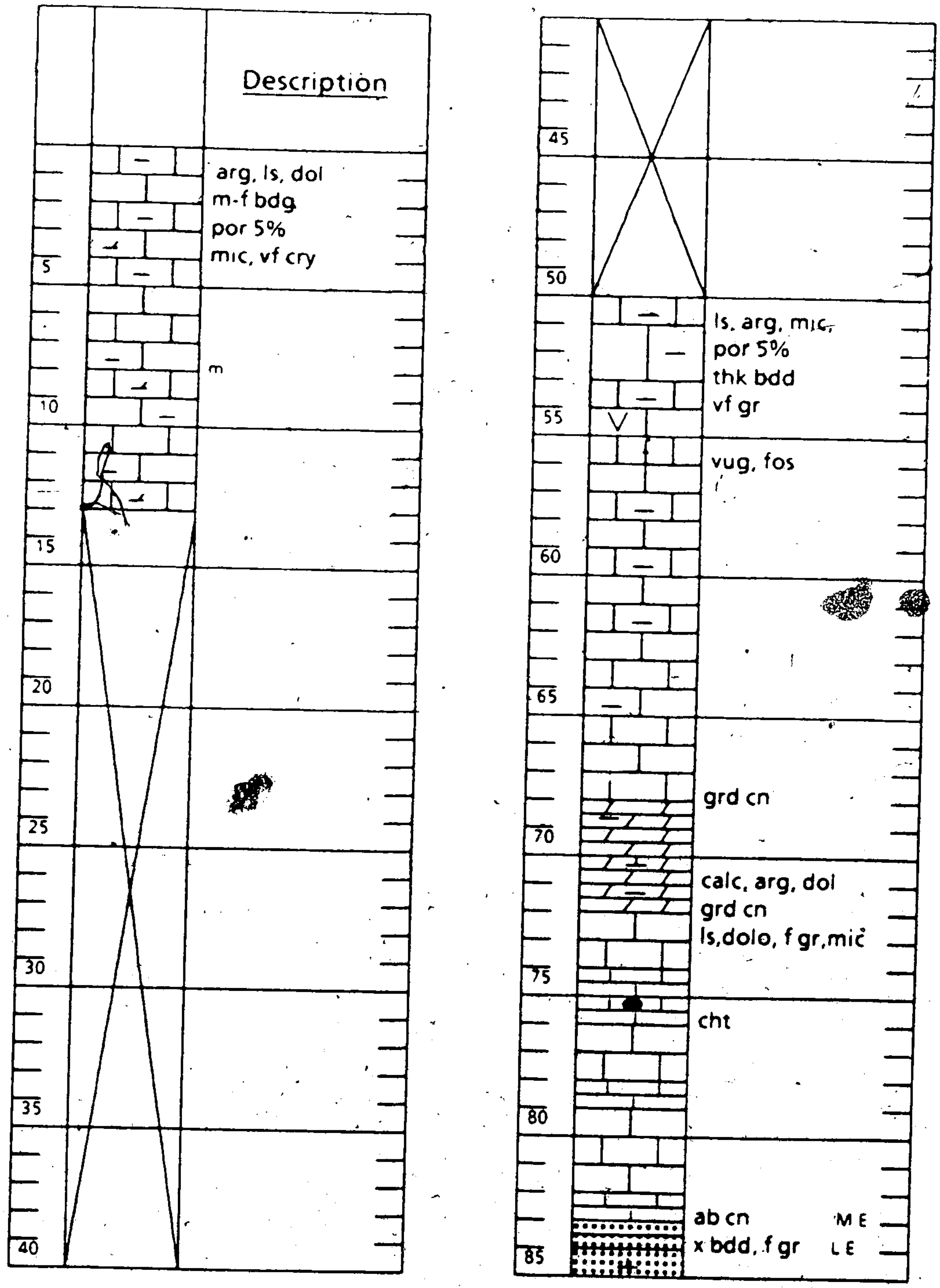


Symbols

Argillaceous	—
Calcareous	⊥
Chert (Nodules, Stringers, Blebs)	●
Conglomerate	O O
Dolomitic	⊥
Fossiliferous	F
Pitted Surface	P
Silty	..
Vuggy	V

Abbreviations

abrupt	ab	limestone	ls
argillaceous	arg	light(er)	lt
bedded	bdd	meter	met
bedding	bdg	micritic	mic
brown	brn	medium	m
calcareous	calc	massive	mas
chert	cht	nodular	nod
color	co	porosity	por
contact	cn	purple	pur
course	c	slight(ly)	sl
conglomerate	cgl	silty	slty
crinoidal	crin	stringer	strg
crystalline	cry	thick	thk
dolomite	dol	thin	thn
fine	f	vug(gy)	vug
fossiliferous	fos	weathered	wthrd
grey	gry	cross-bedded	xbd
grain(ed)	gr	cross-laminated	xlam
grade(ed)	grd	yellow	yel
laminated	lam		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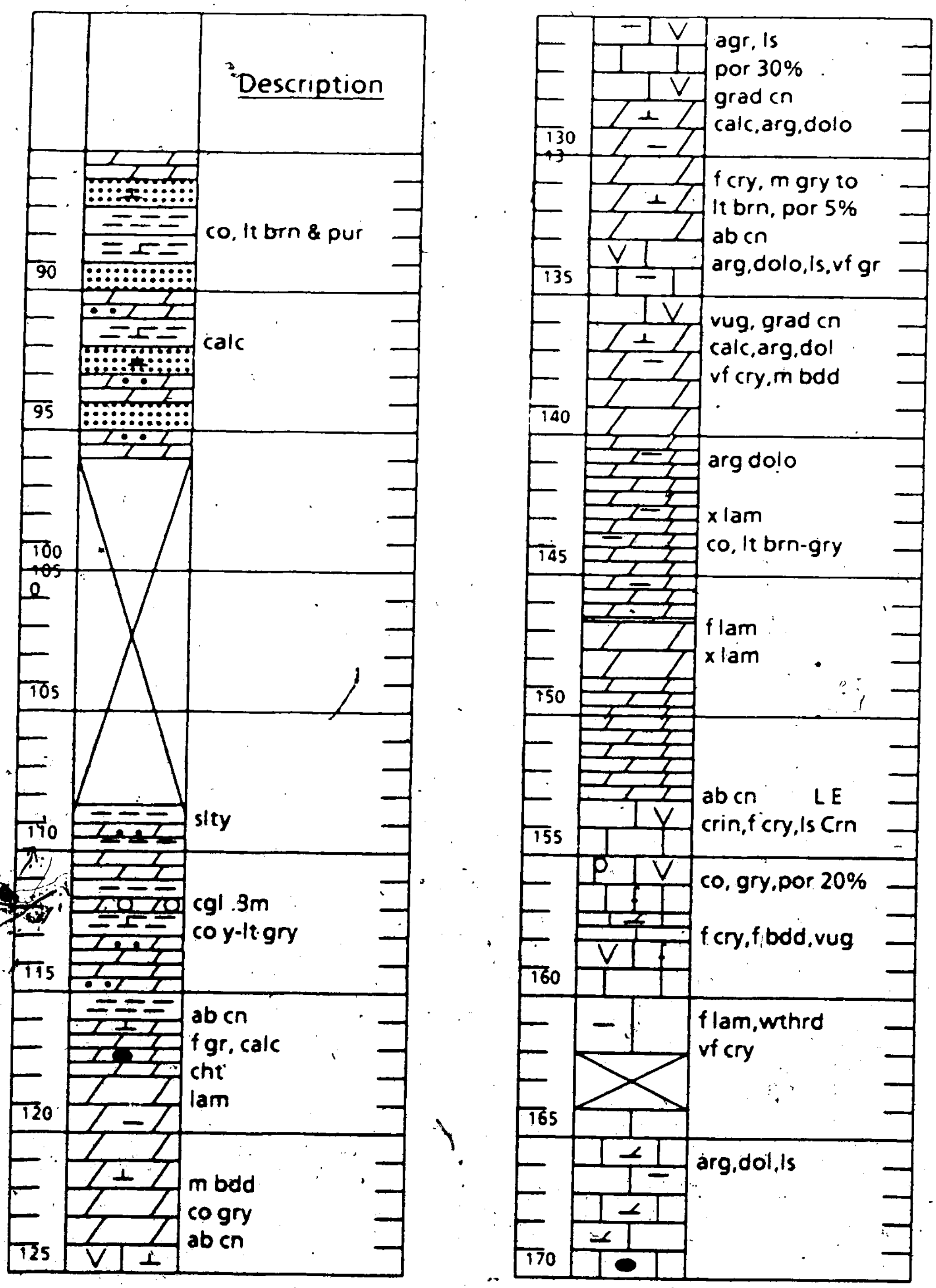
5
10
15
20
25
30
35
40
arg, ls, dol
m-f bdg
por 5%
mic, vf cry
m
45
50
55
60
65
70
75
80
85
ls, arg, mic,
por 5%
thk bdd
vf gr
vug, fos
grd cn
calc, arg, dol
grd cn
ls,dolo, f gr,mic
cht
ab cn
x bdd, f gr
ME
LE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90
calc
95
100
105
sIty
110
cgl .3m
co y-lt gry
115
ab cn
f gr, calc
cht
lam
120
m bdd
co gry
ab cn
125
agr, ls
por 30%
grad cn
calc,arg,dolo
130
f cry, m gry to
lt brn, por 5%
ab cn
arg,dolo,ls,vf gr
135
vug, grad cn
calc,arg,dol
vf cry,m bdd
140
arg dolo
x lam
co, lt brn-gry
145
f lam
x lam
150
ab cn
L E
crin,f cry,ls Crn
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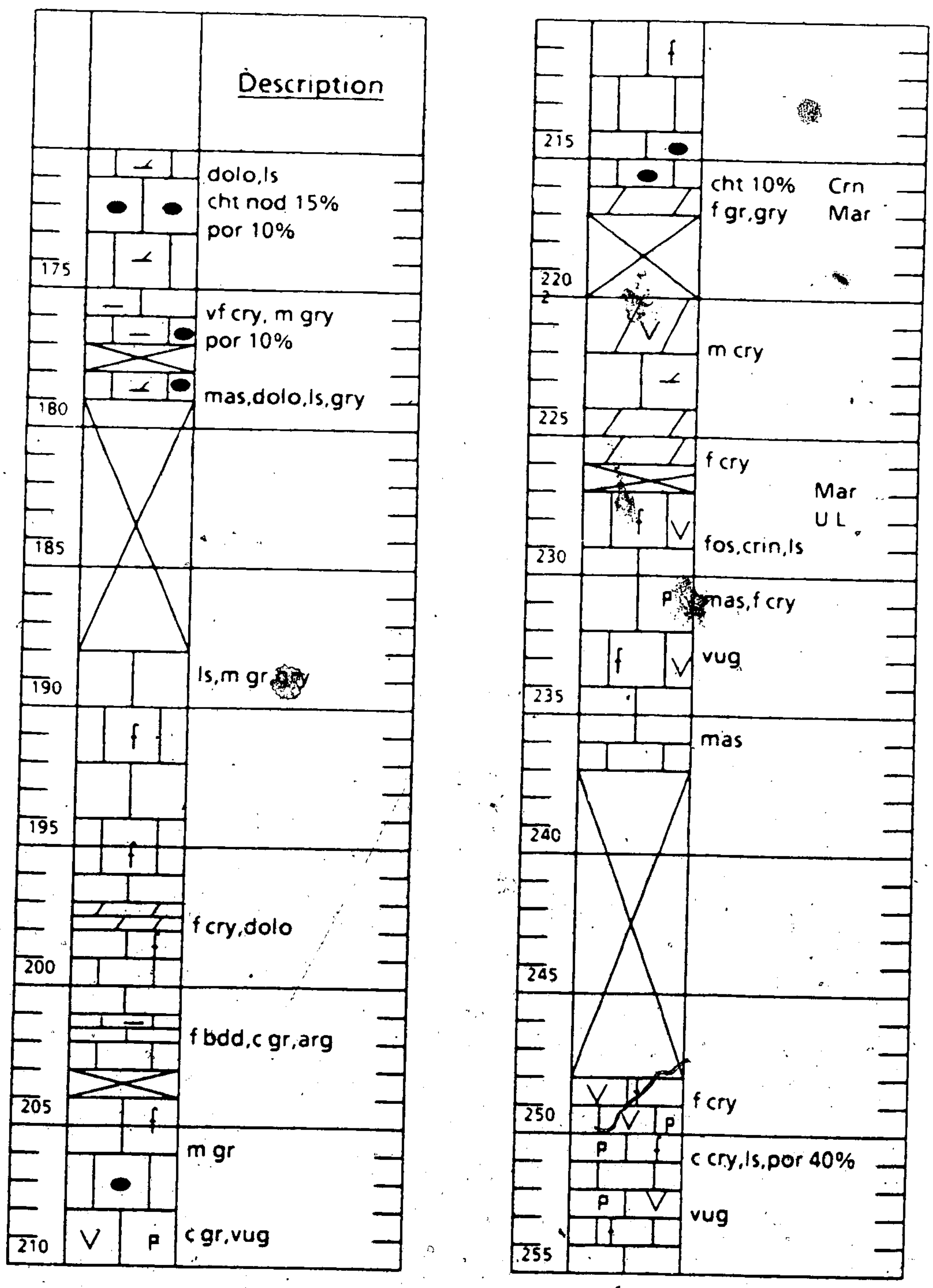
160
f lam,wthrd
vf cry
165
arg,dol,ls
170


Description
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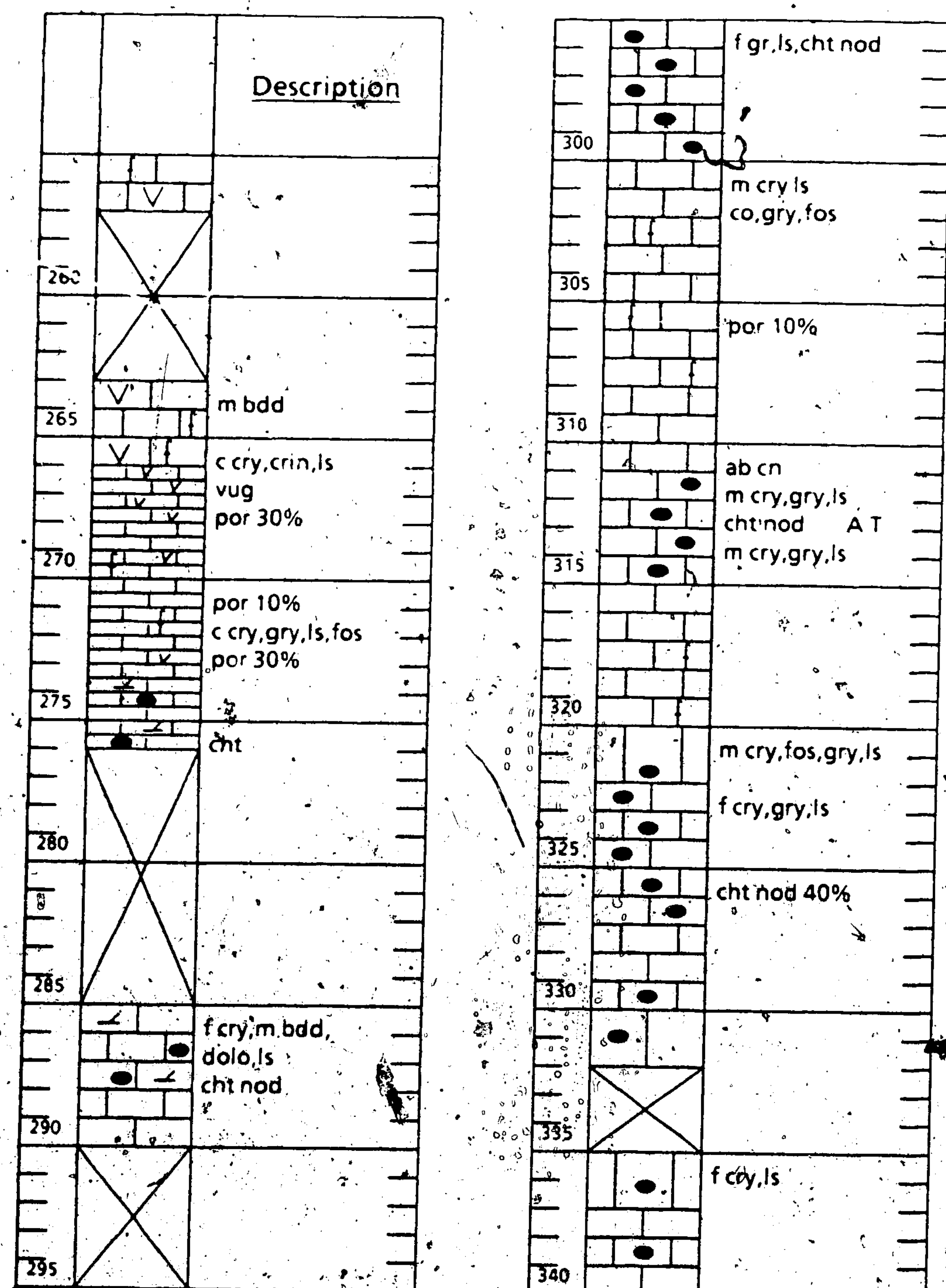
cht nod 15%
por 10%
175
vf cry, m gry
por 10%
mas,dolo,ls,gry
180
185
ls,m gr,gry
190
195
f cry,dolo
200
f bdd,c gr,arg
205
m gr
c gr,vug
210
215
cht 10%
f gr,gry
Crn
Mar
220
m cry
225
f cry
Mar
U L
fos,crin,ls
230
mas,f cry
vug
235
mas
240
245
f cry
250
c cry,ls,por 40%
vug
255


Description
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265
270
275
280
285
290
295
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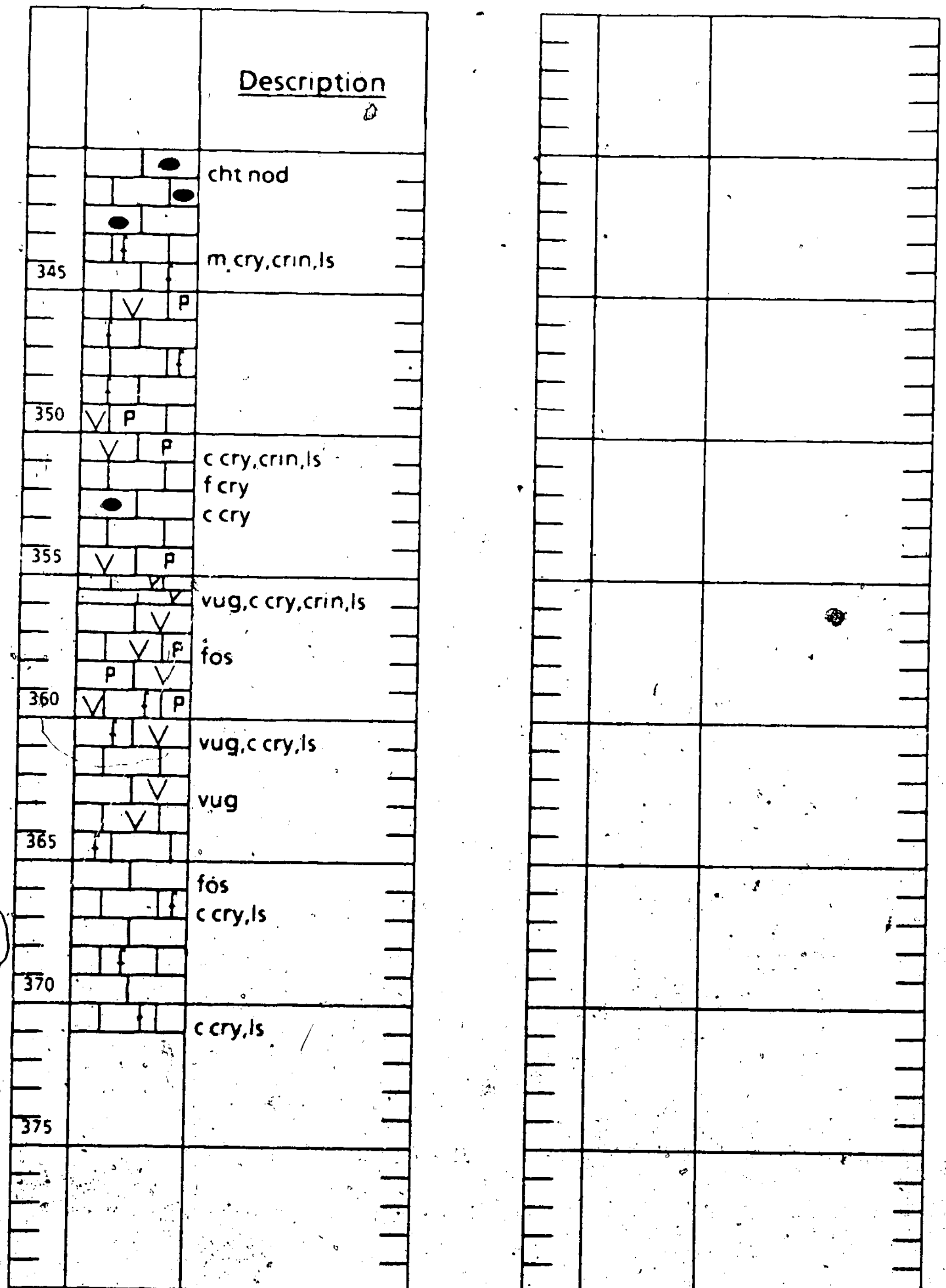
c cry,crin,ls
vug
por 30%
por 10%
c cry,gry,ls,fos
por 30%
cht
f cry,m bdd,
dolo,ls
cht nod
300
305
310
315
320
325
330
335
340
f gr,ls,cht nod
m cry ls
co,gry,fos
por 10%
ab cn
m cry,gry,ls
cht nod
A T
m cry,gry,ls
m cry,fos,gry,ls
f cry,gry,ls
cht nod 40%
f cry,ls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350
c cry,crin,ls
f cry
c cry
355
vug,c cry,crin,ls
fos
360
vug,c cry,ls
vug
365
fos
c cry,ls
370
c cry,ls
375

B. Appendix 2

```
C Basic program for the Casio FX-90 hand computer.
C This program adjusts the raw elevation values,
C linearly for the variation in atmospheric
C pressure, from the first to last reading of the
C day at a benchmark.
C
C CLEAR ALL MEMORY.
C
10   VAC
C
C INPUT THE BENCHMARK STARTING AND ENDING ELEVATIONS
C AND THE STARTING AND ENDING TIME.
C
20   INP "INP ELEV START",A
30   INP "INP ELEV END",B
40   INP "INP TIME START",C
C
C CONVERT TIME IN HOURS AND MINUTES TO DECIMAL
C HOURS.
C
50   C = ( FRAC C * 100 / 60 ) + INT C
60   INP "INP TIME END",D
70   D = ( FRAC D * 100 / 60 ) + INT D
80   G = ( B - A ) / ( D - C )
C
C SURVEYED ELEVATION OF BENCHMARK = 1398 METERS
C
90   X = 1398 - A
100 I = 0
C
C INPUT TIME OF READING AND ELEVATION AT OUTCROP
C
110 INP "TIME",T
120 I = I + 1
130 T = ( FRAC T * 100 / 60 ) + INT T
140 INP "ELEV",E
150 K = E + X - ( ( A - C ) * G )
C
C PRINT ADJUSTED ELEVATION FOR OUTCROP
C
160 PRT K
170 IF I LT 50 THEN 110
180 END
```

C. Appendix 3

TECTRONIX PROCEDURE FOR PLACING MAP DATA IN TRIPOD FILES

A. TERMINAL SET-UP TECTRONIX T 4016-1

1. Press switches TTY down, & MARGIN CONTROL off.
2. Turn on terminal. Wait 5 min. for terminal to warm up.
3. Press RESET PAGE key.
4. Switch Gandalf ON & enter T4010 in response to ENTER TERMINAL ID.
5. Sign On.
6. Press top LH switch to LOCAL, press ECS key, type : ,press top LH switch to LINE, & press RESET PAGE.

B. GRAPHICS TABLET SET-UP & DATA ENTRY

1. Type SO TX1. The file TX1 consists of following run file :

```
$EMPTY DATA1 OK
$RUN WYERRF.L# 2=DATA1(*L+1) 5=*MSOURCE*
                    7=-OUTPUT
$SOURCE *MSOURCE*
```

2. Type (5X, 2F10.1) in answer to ENTER FORMAT FOR OUTPUT FILE
3. Place the map on the graphics tablet the location of the point with the maximum X & Y value is in the top right hand corner. Define a square on the map and number the corners 1 to 4 going CCW starting at the top lefthand corner.
4. In answer to the *ENTER XMIN & YMIN: enter the map coordinates of point 2 (e.g. 343000.,24300.) RETURN and for *ENTER XMAX & YMAX: the map coordinates of point 4 (e.g. 585000.,122000.) RETURN.

   Note: Coordinates should have values such as 568000 & not 568641. Should you mistakenly type incorrect values & obtain an error message, type [& begin again at step 4. Should you mistakenly type incorrect values & not obtain an error message, begin again at step 1.

5. Digitize points 1, 2, 3 & 4 in order then press BREAK then RETURN.
6. Respond appropriately to message ending IF YOU WISH TO REDIGITIZE POINTS 1-4 by typing REDO or pressing RETURN, which returns you to step 5.

7. Digitize points 1,2 on the menu in order and press BREAK then RETURN.
   1) Type TITLE in answer to *ENTER COMMAND *
   2) Answer *ENTER TITLE: * by typing title e.g. ROBB SET 1
   3) Answer *ENTER COMMAND * with RUN and press RETURN.

8. To digitize data use one of the following procedures.

For a data point on **surface trace** of a geologic structure,

1) place cursor over menu rectangle labelled CONTACT & press button,
2) place cursor over rectangle labelled FORMATION & press button,
3) place cursor over square labelled with letter, number or symbol chosen to identify geologic structure & press button,
4) place cursor over rectangle labelled **ELEVATION** & press button,
5) place cursor successively over squares labelled with numbers specifying elevation of point, pressing button after each move, &
6) place cursor over data point on the map & press button

If data point is a **strike-and-dip** symbol for a planar structure,

1) place cursor over point inside menu rectangle labelled **BEDDING, CLEAVAGE** or **FAULT** & press button,
2) place cursor over rectangle labelled FORMATION & press button,
3) place cursor over square labelled with letter, number or symbol chosen to identify rock unit exposed at outcrop & press button,
4) place cursor over rectangle labelled **ELEVATION** & press button,
5) place cursor successively over squares labelled with numbers specifying elevation of point, pressing button after each move,
6) place cursor over rectangle labelled **WAY UP** & press button,
7) place cursor over square labelled 0, 1 or 2 if way up of strata is unknown or irrelevant, right-way-up, or overturned, respectively,
8) place cursor over rectangle labelled **DIP** & press button,

9) place cursor successively over squares labelled with numbers specifying the dip, pressing button after each move, &

10) place cursor successively over LH & RH ends of strike line, looking in direction of dip, pressing button after each move

If data point is a trend-and-plunge symbol of a linear structure,

1) place cursor over point inside menu rectangle labelled FOLD, STRIAE or LINEATION & press button,
2) place cursor over rectangle labelled FORMATION & press button,
3) place cursor over point inside square labelled with letter or number, chosen to identify rock unit exposed at outcrop & press button,
4) place cursor over rectangle labelled ELEVATION & press button,
5) place cursor successively over squares labelled with numbers specifying elevation of point, pressing button after each move,
6) place cursor over rectangle labelled PLUNGE & press button,
7) place cursor successively over squares labelled with numbers specifying plunge, pressing button after each move, &
8) place cursor successively over rear & front ends of arrow, pressing button after each move.

IMPORTANT

1) After every 15 minutes, press BREAK & RETURN, & return to step 12

2) If value used to specify e.g. FORMATION is the same for a series of data points, it need be specified only once.

3) To edit data entered using the above procedures, press BREAK then RETURN twice before typing MT.

C. GRAPHICS TABLET INTERPRETATION

1. Type SO TX2. The file TX2 consists of the following run command:

```
$EMPTY DATA2 OK
$RUN WYNN:SCAN.OBJ 3=WYNN:MENU 5=DATA1
6=DATA2(*L+1)
$SOURCE *MSOURCE*
```

The program TX2 uses the file created in TX1 as input and interperates the map coordinate values as data points and menu items. The file DATA2 is an interpreted version of DATA1 and should be listed and checked for errors such as blank lines not followed by a title & menu variables such as elevation called but not followed by a number, & edited appropriately.

D. FORMATING FILES FOR INPUT INTO "TRIPOD".

1. Type SO TX3. The file TX3 consists of the following run command:

```
$EM -FORMA
$EM -FORMB
$RUN OUTPUT.OBJ+WYNN:ERRF.OBJ1 1=DATA2
3=WYNN:MENU 5=*MSOURCE* 6=*MSINK* 7=-FORMA
8=-FORMB
$IF RC=0 $COPY -FORMA TO MA(*L+1)
$IF RC=0 $COPY -FORMB TO MB(*L+1)
```

2. The files -FORMA & -FORMB have the same content & format as outcrop files prepared from completed copies of Form A & Form B used in conjunction with the TRIPOD package. If no errors were encountered in processing the file DATA2 (RC=0) these files are added to the permanent files MA & MB. In answer to ENTER NEXT OUTCROP NUMBER (I4 FORMAT), type "0001" the first time data are being entered into MA & MB. During subsequent runs, enter e.g. "0102" if the number of the last outcrop in the existing files MA & MB is 101. If an error was encountered, edit DATA2 & retype SO TX3.

E. TERMINAL POWER-DOWN, TECTRONIX 4016-1

1. At the end of a session type SIG, press RESET PAGE key, turn top LH switch to LOCAL, turn Gandalf OFF, turn top LH switch to LINE, & turn power off.

D. Appendix 4

The program ORIENT (H.A.K. Charlesworth, 1983) rotates data and produces rose diagrams, scatter plots, and pi-diagrams from structural orientation data. ORIENT is divided into two parts. Program A is an interactive question and answer program that produces a command file which is then used by program B to process the data and produce output. ORIENT can process upto 1000 data points at a time of either planar or linear orientations, specified in dip-direction and dip or trend and plunge respectively. ORIENT is written in Fortran77 and runs on the Michigan Terminal System at the University of Alberta.

To get a more accurate pi-diagram for the kinematic study of Turtle Mountain it was nessisary to write the subroutine DNSPLT. This replaced the program in ORIENT that produced orientation diagrams. DNSPLT allowed the counting locations of a pi-diagram to be increased from 277 to 2901 on a 20 cm. diameter stereonet. An option for either a stereographic projection or equal-area projection was added as well as a choice of either a contoured diagram or a diagram where the percentage at each counting location is represented by a different symbol from 1 to 100 percent. The two diagrams at the end of the appendix 3 show the different types of diagrams available. Finaly to make the ORIENT package more useful to the field geologist the package was rewitten to run on an IBM-PC with a hard copy available on an Epson FX80 printer.

```
                         SUBROUTINE DNSPLT
*
* COPYRIGHT (C) 1984 K. FOSSEY & H.A.K. CHARLESWORTH
*
* Subroutine prints square matrix of symbols. Square
* circumscribes circle of radius 10 cm. Elements in matrix
* outside circle are blank. Elements inside circle mark
* projections of counting circles. Where % of points inside
* counting circle are less than 1, a point is printed.
* Where % is greater than 1, a symbol is printed which
* represents a percentage or range of percentages, as
* specified by user. Spacing of elements in matrix can be
* close or open.
```

```
*
* Common Block for orient2 program.
*
      COMMON /ORCHAR/ CSID, ID, NAME, TYPE
      CHARACTER*1 TYPE
      CHARACTER*4 CSID
      CHARACTER*10 DATAF, INST, LIST1, PIDI1
      CHARACTER*40 ID, NAME
      COMMON /ORINT/ CONT, NCONT, NDC, NP, NTP, TP
      INTEGER CONT(9), NCONT, NDC, NP, NTP, TP(2000)
      COMMON /ORLOG/ CPS, DEN, HST, IGN, LST, MAS, MOV,
     1               ROT, RSE, SCT, SMO, STR, WLF, CON
      LOGICAL CPS, DEN, HST, IGN, LST, MAS, MOV, ROT, RSE,
     1        SCT, SMO, STR, WLF, CON
      COMMON /ORREAL/ DCD, PARH, PARM, PARS, PP, RDATA,
     1               SCAL, SCALE, T
      REAL DCD(3000), PARH, PARM, PARS, PP, RDATA(3), SCAL,
     1               SCALE, T(9)
*
* Declaration of subroutine variables.
*
      CHARACTER*1 CNTINT(10), ND(79), SYMB(102)
      INTEGER FIR(10), I, IP, J, KOUNT, L, M, NX, NY,
     1        SEC(10)
      REAL AD, AL, AM, AN, COSP, CPHI, PI, PL, R,
     1 RAD, RAD2, R2, SX, SY, TEST, TR, X, Y, Y1, YR
*
* Data statements for subroutine.
*
      DATA CNTINT /'1','2','3','4','5','6','7','8','9','0'/
      DATA PI /3.14159/, RAD /39.37/, RAD2 /1550./
*
* Calculate TEST, cosine of radius of counting circle.
*
      TEST = 1. - PP / 100.
*
* Create a CONTOURED density diagram or a NUMERICAL density
* diagram
*
      IF (CON) THEN
*
* Create arrays FIR & SEC such that e.g. FIR(3) & SEC(3)
* specify range of percentages represented by symbol
* CNTINT(3), i.e. 8.
*
        FIR(1) = 1
        SEC(NCONT+1) = 100
        DO 48 I = 1,NCONT
          SEC(I) = CONT(I) - 1
          FIR(I+1) = CONT(I)
48      CONTINUE
```

```
*
* Create array SYMB. SYMB(3) - SYMB(102) specify symbols
* representing percentages 1, 2, 3 ...100.
*
          DO 49 J = 1, NCONT+1
            DO 51 I = FIR(J)+2, SEC(J)+2
              SYMB(I) = CNTINT(J)
   51       CONTINUE
   49     CONTINUE
          SYMB(1) = ' '
          SYMB(2) = '.'
          IP = IFIX (PP)
*
* Write density diagram header for either the stereographic
* or equal area net.
*
          IF (WLF) THEN
            WRITE (7,95) NP, IP, (CONT(I), I = 1, NCONT)
          ELSE
            WRITE (7,100) NP, IP, (CONT(I), I = 1, NCONT)
          ENDIF
        WRITE (7,'(A40)') NAME
      ELSE
*
* Data for the symbols that represent numerical percentage
* of a counting location from 1 to 100%
*
          DATA SYMB /' ','.','1','2','3','4','5','6','7',
     1    '8','9','0','A','B','C','D','E','F','G','H','I',
     2    'J','K','L','M','N','O','P','Q','R','S','T','U',
     3    'V','W','X','Y','Z','a','b','c','d','e','f',
     4    'g','h','i','j','k','l','m','n','o','p','q',
     5    'r','s','t','u','v','w','x','y','z','*','*','*',
     6    '*','*','*','*','*','*','*','*','*','*','*','*',
     7    '*','*','*','*','*','*','*','*','*','*','*','*',
     8    '*','*','*','*','*','*','*','*','*','*','*','*'/
          IP = IFIX (PP)
*
* Write density diagram header for either the stereographic
* or equal area net.
*
          IF (WLF) THEN
            WRITE (7,110) NP, IP
          ELSE
            WRITE (7,120) NP, IP
          ENDIF
          WRITE (7,'(A40)') NAME
      END IF
*
```

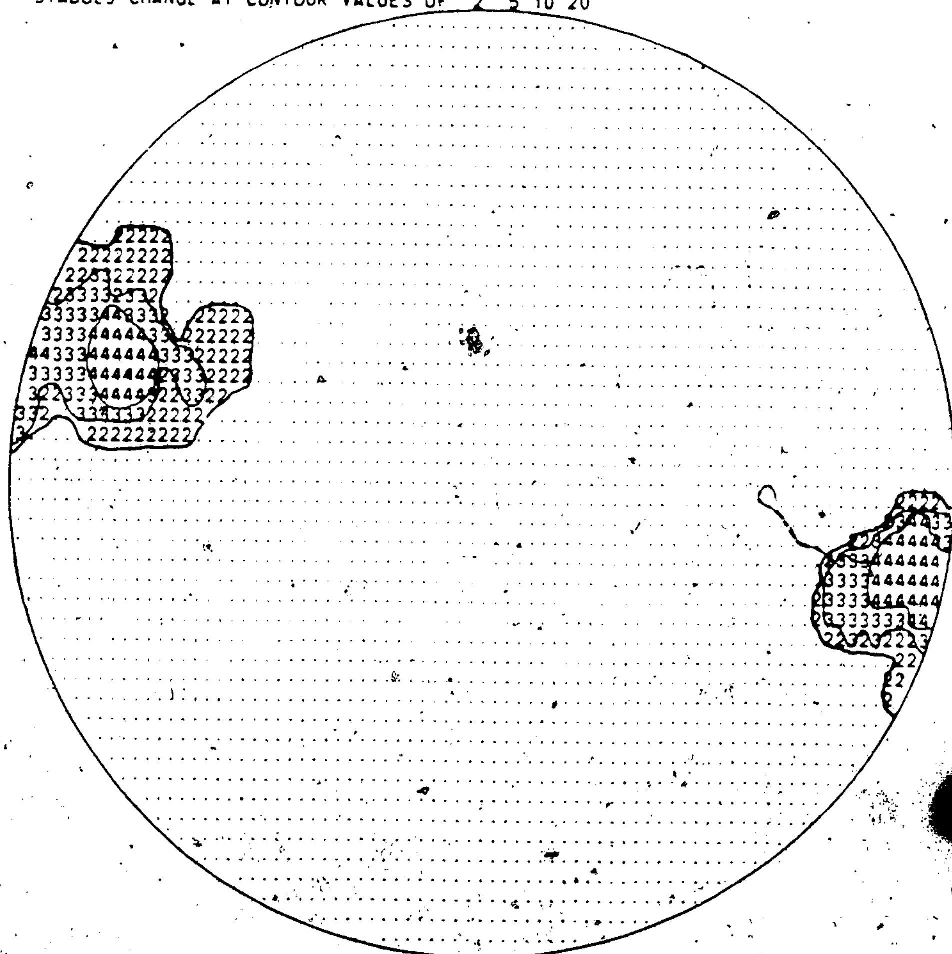
```
* Find coordinates (X,Y1), trend (TR) & plunge (PL), &
* direction cosines (AL,AM,AN) of counting locations.
* Spacing of characters in Y direction is 1.6667 times
* spacing in X.
*
      IF (CPS) THEN
        SY = 1.
        SX = 1.
        NY = 47
        NX = 79
      ELSE
        SY = 2.
        SX = 3.
        NY = 24
        NX = 27
      ENDIF
      Y = 23 + SY

      DO 30 J = 1,NY
        Y = Y - SY
        X = - 39 - SX
        DO 20 L = 1,NX
          M = 1
          X = X + SX
          Y1 = Y * 1.6667
          R2 = X * X + Y1 * Y1
          R = SQRT (R2)
*
* Calculate if the counting location is inside a 10 cm.
* radius circle, then calculate the direction cosine of the
* counting location.
*
          IF (R2 .LE. RAD2) THEN
            M = 2
            IF (Y .EQ. 0) THEN
              IF (X .GE. 0) THEN
                TR = PI / 2
              ELSE
                TR = 3 * PI / 2
              END IF
            ELSE
              TR = ATAN ( X / Y1 )
              IF (Y .LT. 0) TR = TR + PI
            END IF
            IF (WLF) THEN
              PL = 2 * ATAN ((RAD - R) / (RAD + R))
            ELSE
              PL = ASIN(1 - (R2)/RAD2)
            END IF
```

```
         COSP = COS(PL)
         AL = COS(TR) * COSP
         AM = SIN(TR) * COSP
         AN = SIN(PL)
*
* Count orientations within PP% area around counting
* locations
*
         KOUNT = 0
         DO 10 I = 3, NDC, 3
           CPHI = ABS(AL*DCD(I - 2) + AM*DCD(I - 1) +
     1            AN*DCD(I))
           IF (CPHI .GE. TEST) KOUNT = KOUNT + 1
   10    CONTINUE
         M = M + KOUNT * 100. / NP
       END IF
       ND(L) = SYMB(M)
   20 CONTINUE
*
* Write line of density printout on file attached to unit 7
*
      IF (CPS) THEN
        WRITE (7,'(79A1)') ND
      ELSE
        WRITE (7,'(A,26A3,/)') (ND(I), I = 1,27)
      ENDIF
   30 CONTINUE
      IF (.NOT. CPS) BACKSPACE 7
      RETURN
*
* format statements for density diagram headers.
*
   95 FORMAT (' PERCENTAGES OF', I4, ' POINTS IN', I2,
     1 '% AREA OF HEMISPHERE. STEROGRAPHIC PROJECTION.', /,
     2 '   SYMBOLS CHANGE AT CONTOUR VALUES OF', 9I3)
  100 FORMAT (' PERCENTAGES OF', I4, ' POINTS IN', I2,
     1 '% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.', /,
     2 '   SYMBOLS CHANGE AT CONTOUR VALUES OF', 9I3)
  110 FORMAT (' PERCENTAGES OF', I4, ' POINTS IN', I2,
     1 '% AREA OF HEMISPHERE. STEROGRAPHIC PROJECTION.', /,
     2 '   SYMB : 1%-10%=1-0, 11%-36%=A-Z, 37%-62%=a-z,',
     3 ' 63%-100%=*')
  120 FORMAT (' PERSENTAGES OF', I4, ' POINTS IN', I2,
     1 '% AREA OF HEMISHPERE. EQUAL AREA PROJECTION.', /,
     2 '   SYMB : 1%-10%=1-0, 11%-36%=A-Z, 37%-62%=a-z,',
     3 ' 63%-100%=*')
      END
```

E. Appendix 5

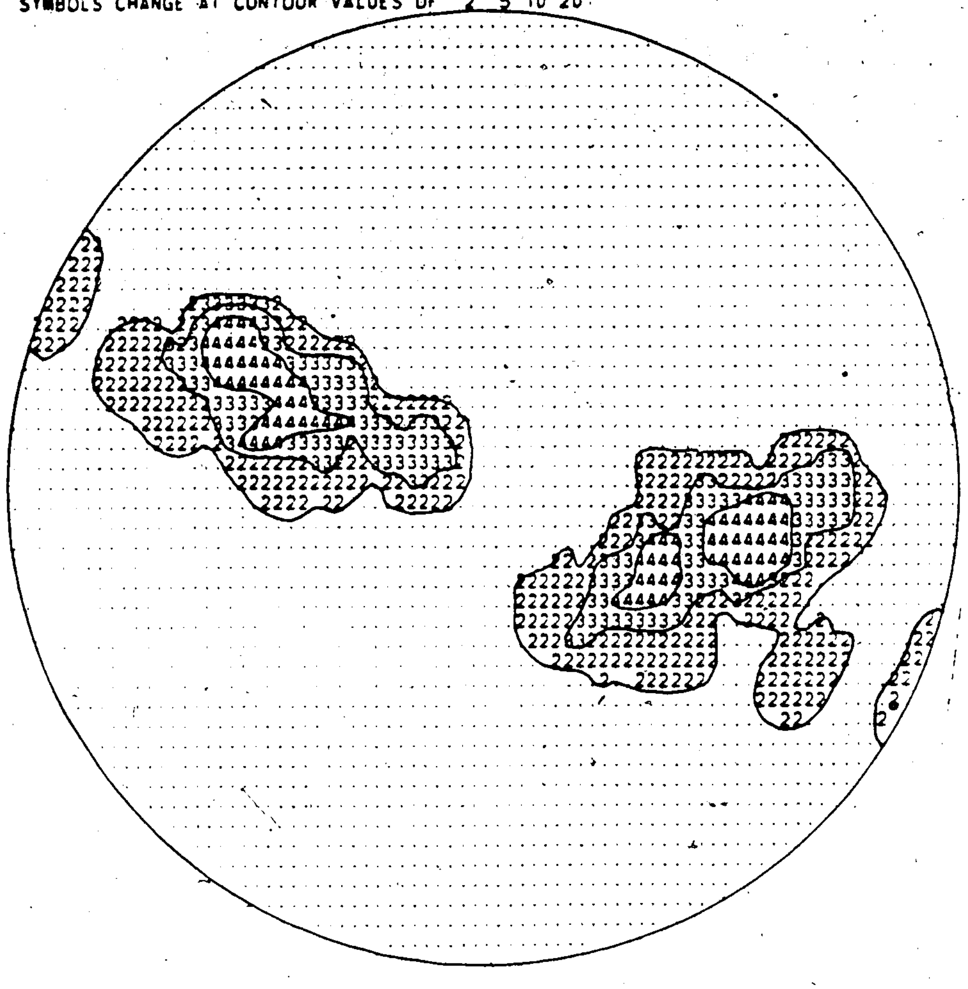
Both structural and slope stability domain high density equal area pi-diagrams are contained in this Appendix. The structural domains pi-diagrams of bedding orientations are illustrated with their eigenvalues and eigenvectors. The minimum eigenvector associated with the minimum eigenvalue gives an estimate of the orientation of the fold axis in the cylindrically folded domains. The slope stability domains pi-diagrams of bedding are also illustrated with their eigenvalues and eigenvectors. The maximum eigenvector associated with the maximum eigenvalue gives an estimate of the orientation of planar bedding in the domain.

STRUCTURAL DOMAIN 1 RUNDLE
PERCENTAGES OF 17 POINTS IN 1.% AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



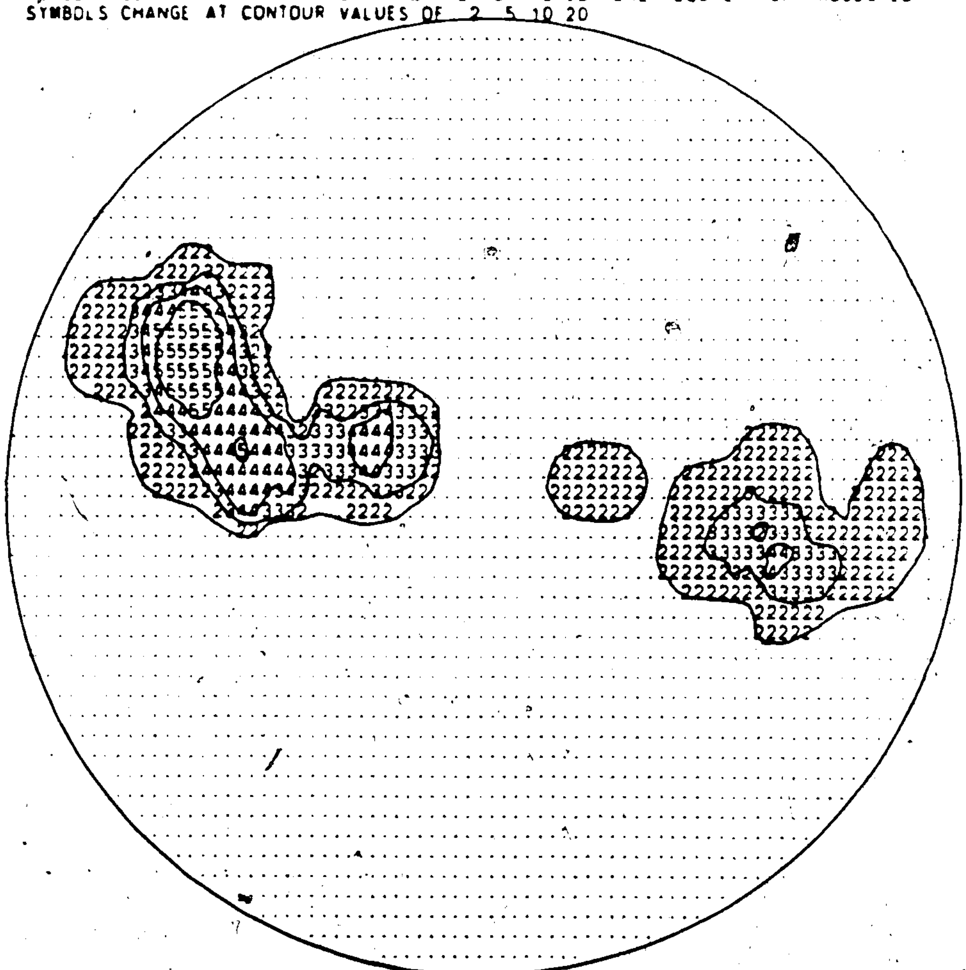
TREND	PLUNGE	EVAL	EVAL/N
286	6	15.6360	0.9198
54	80	1.2711	0.0748
196	8	0.0929	0.0055

STRUCTURAL DOMAIN 2 RUNDLE
PERCENTAGES OF 46 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



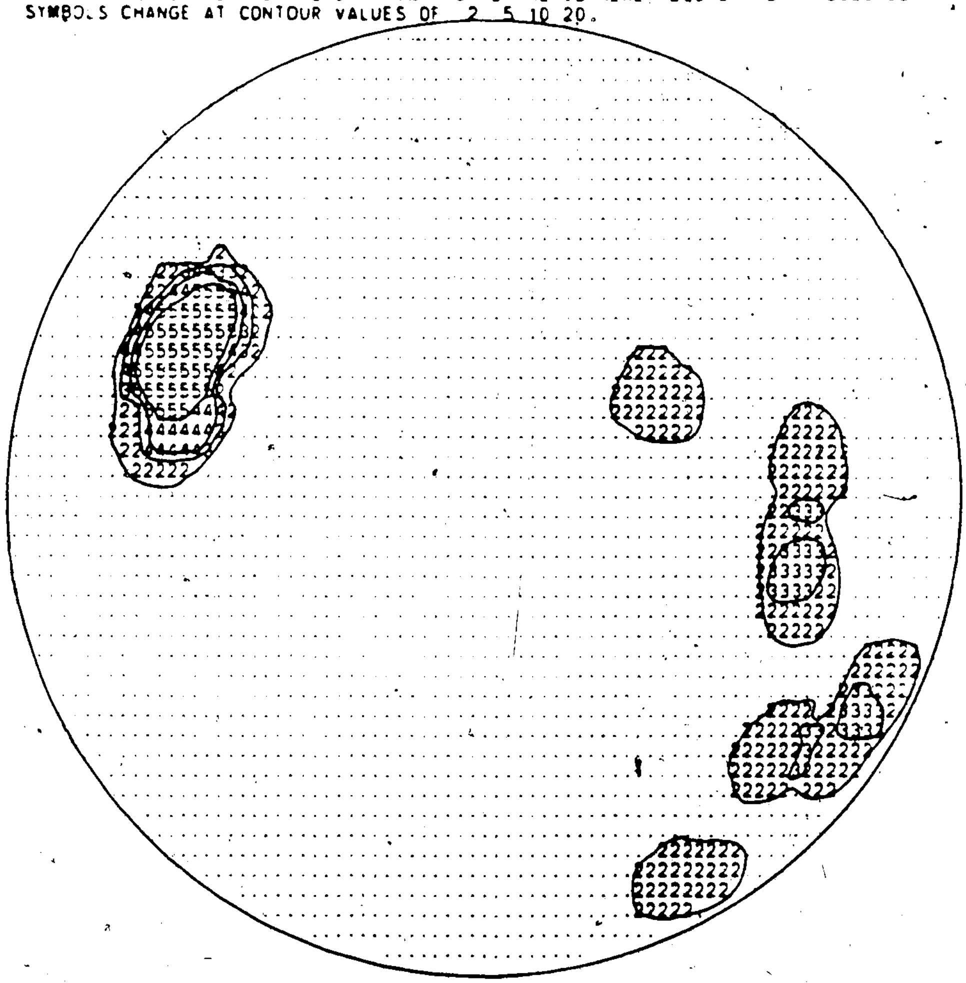
TREND	PLUNGE	EVAL	EVAL/N
108	73	25.4096	0.5524
290	17	19.6317	0.4268
200	1	0.9581	0.0208

STRUCTURAL DOMAIN 3 RUNDLE
PERCENTAGES OF 49 POINTS IN 1 % AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



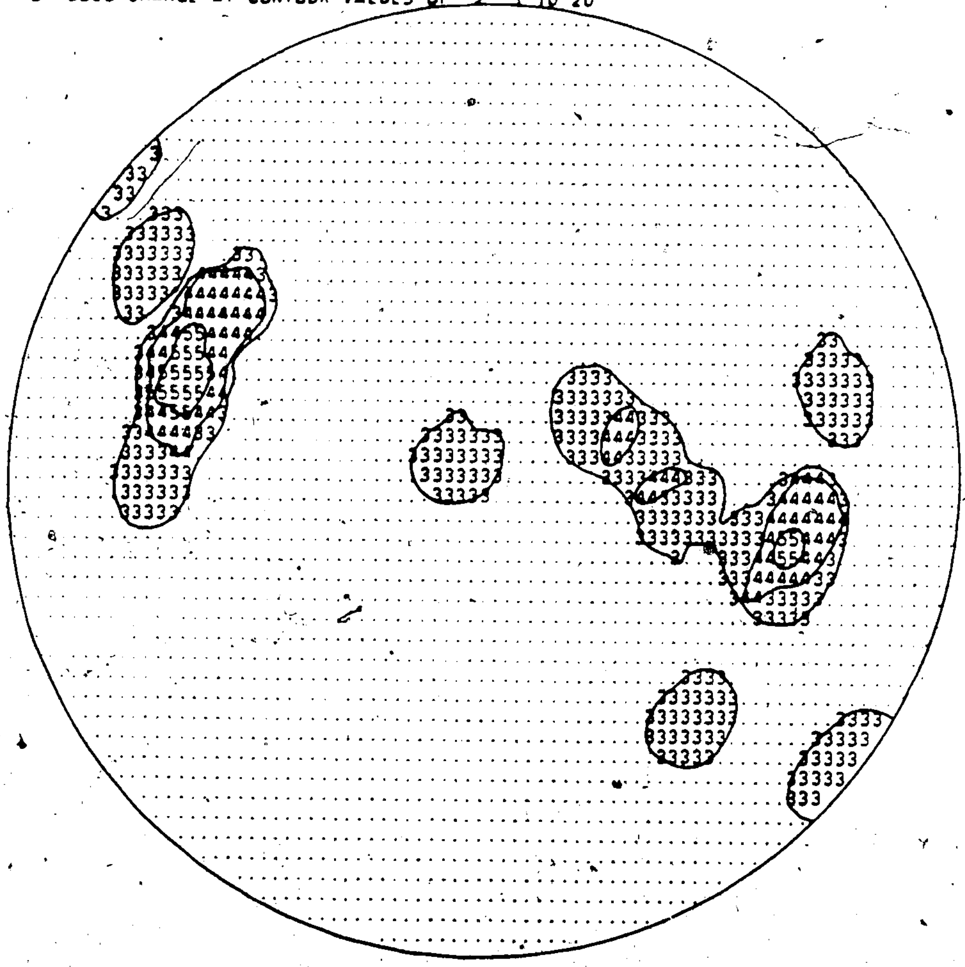
TREND	PLUNGE	EVAL	EVAL/N
290	38	35.9946	0.7346
101	51	12.3101	0.2512
196	4	0.6948	0.0142

STRUCTURAL DOMAIN 4 RUNDLE
PERCENTAGES OF 25 POINTS IN 1.% AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20.



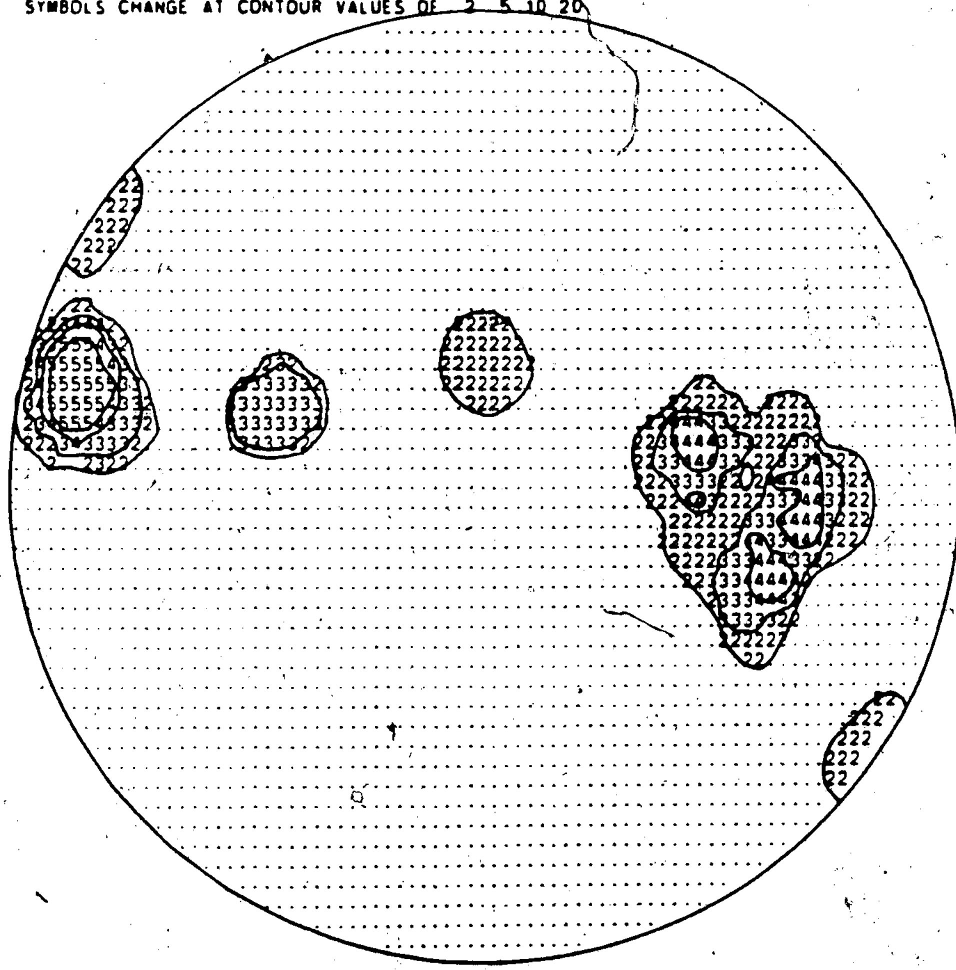
TREND	PLUNGE	EVAL	EVAL/N
295	20	19.7867	0.7915
96	68	4.1704	0.1668
203	7	1.0428	0.0417

STRUCTURAL DOMAIN 5 RUNDLE
PERCENTAGES OF 19 POINTS IN 1 % AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



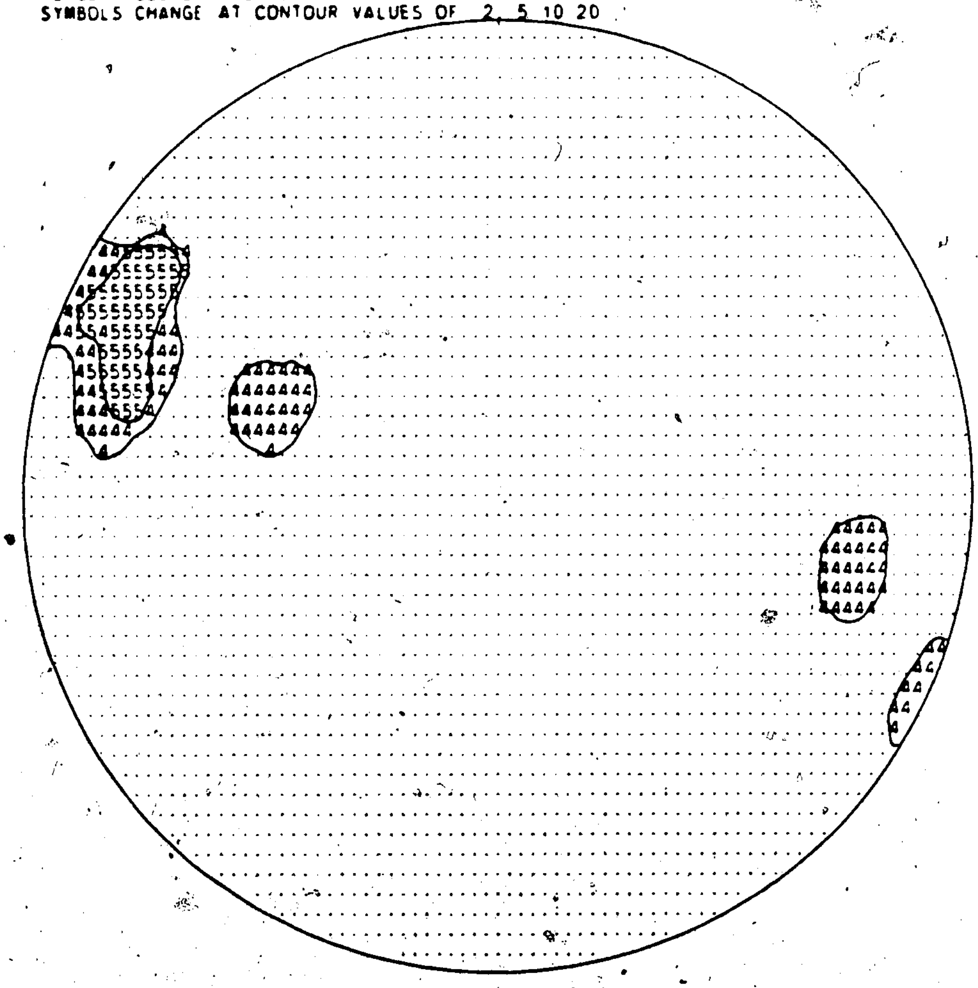
TREND	PLUNGE	EVAL	EVAL/N
108	2	10.9045	0.5739
359	83	7.2567	0.3819
199	7	0.8387	0.0441

STRUCTURAL DOMAIN 6 RUNDLE
PERCENTAGES OF 23 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



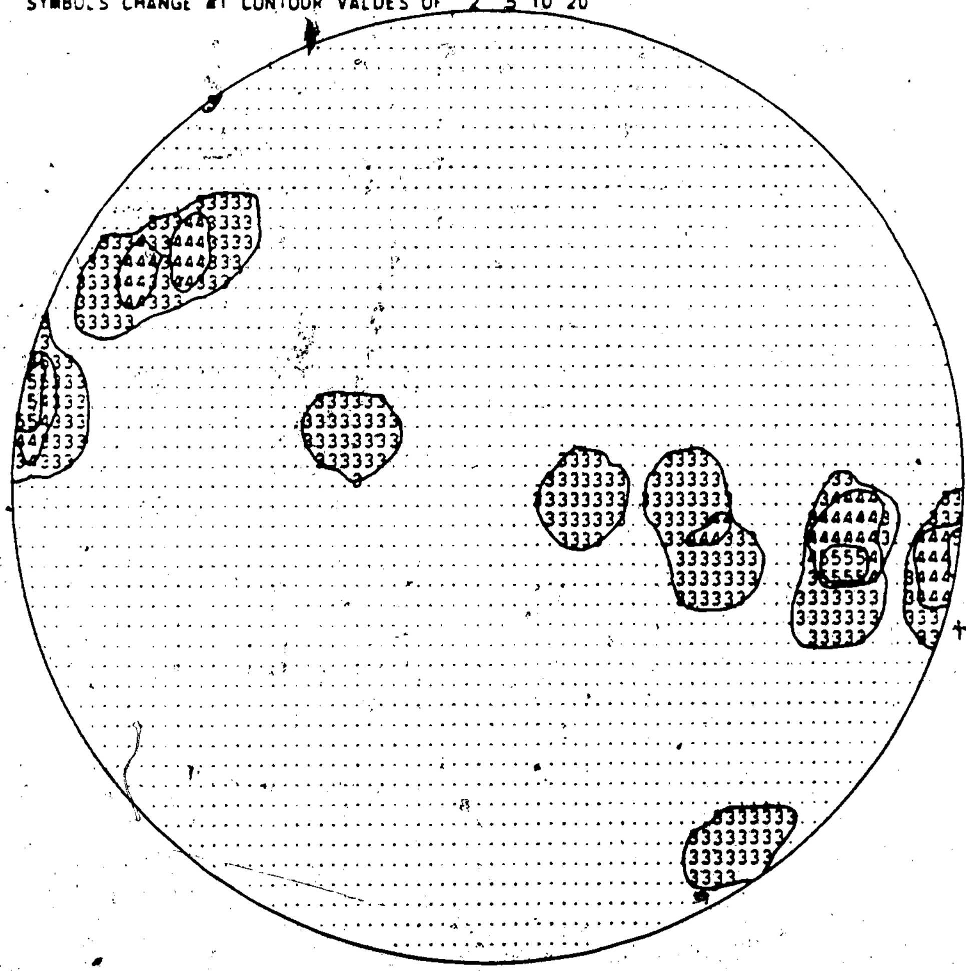
TREND	PLUNGE	EVAL	EVAL/N
101	15	15.7836	0.6862
317	72	6.7837	0.2949
194	10	0.4327	0.0188

STRUCTURAL DOMAIN 7 RUNDLE
PERCENTAGES OF 8 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2, 5 10 20



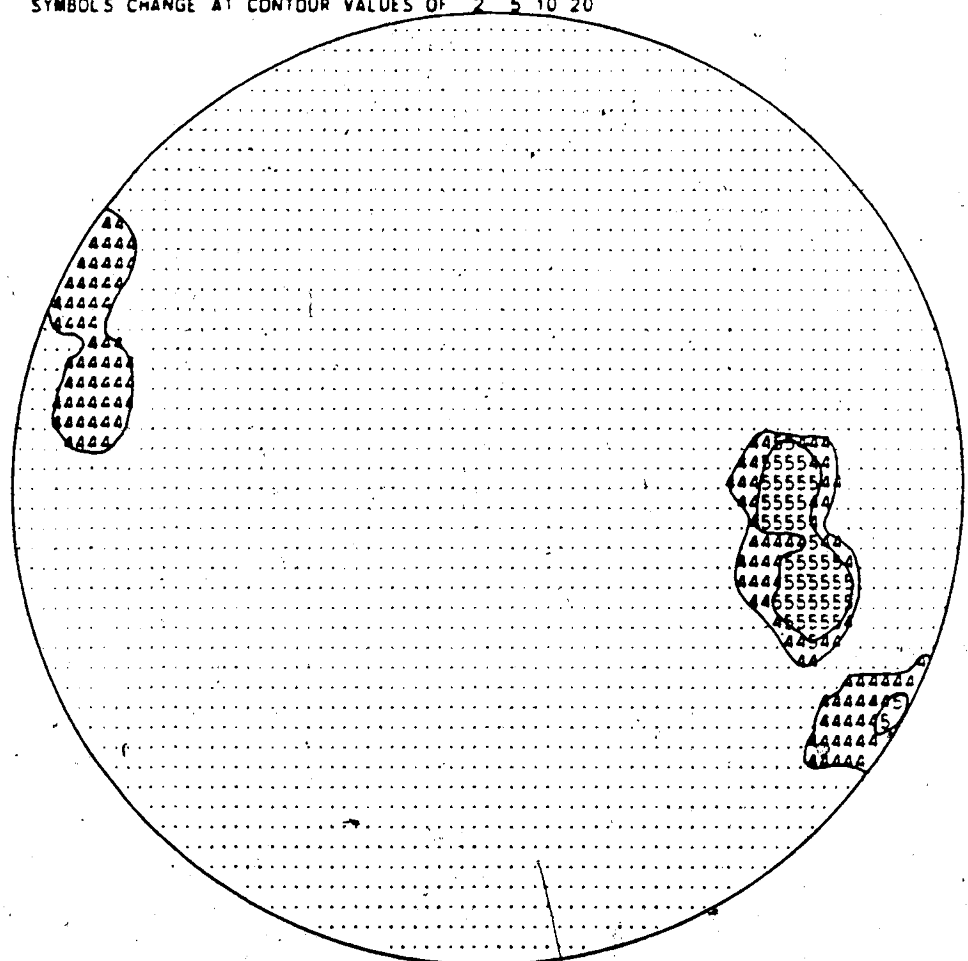
TREND	PLUNGE	EVAL	EVAL/N
292	13	7.1788	0.8974
89	76	0.7437	0.0930
201	5	0.0775	0.0097

STRUCTURAL DOMAIN B RUNDLE
PERCENTAGES OF 14 POINTS IN 1 % AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



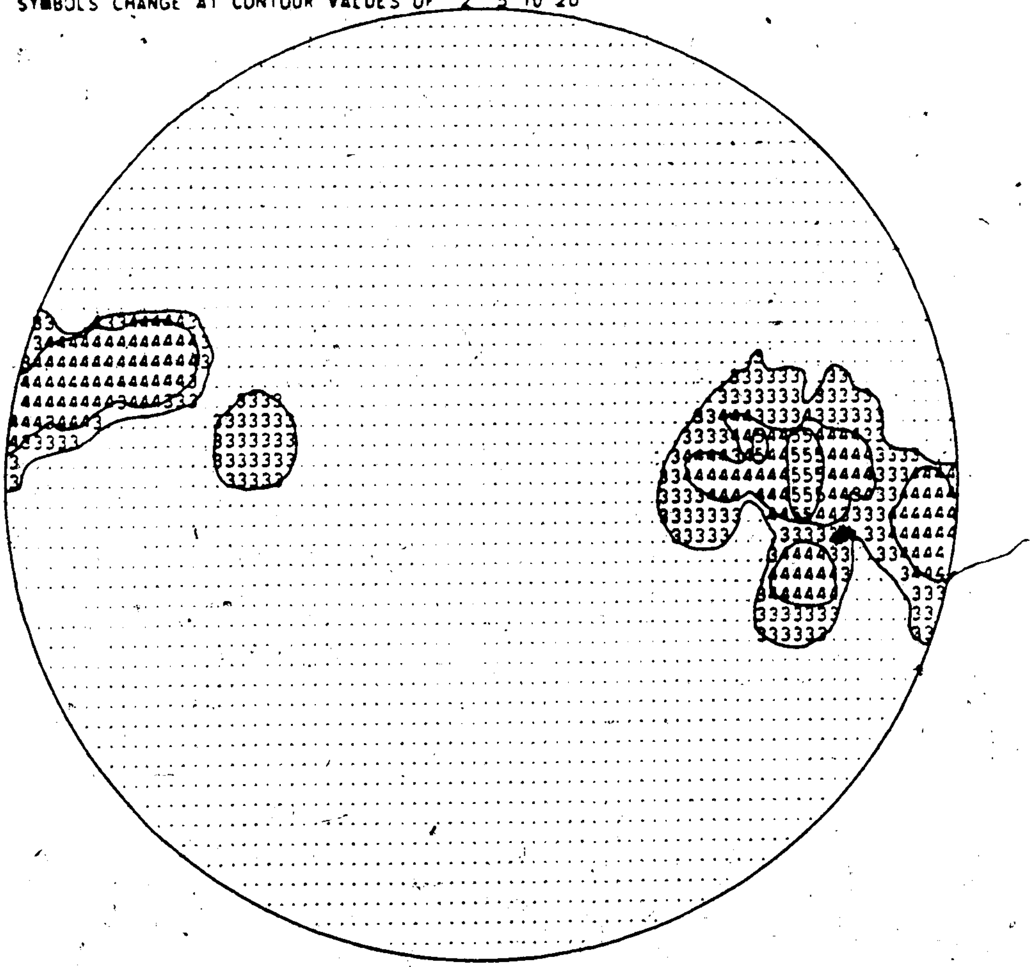
TREND	PLUNGE	EVAL	EVAL/N
111	11	9.7847	0.6989
330	76	3.5992	0.2571
202	8	0.6160	0.0440

STRUCTURAL DOMAIN 9 RUNDLE
PERCENTAGES OF 8 POINTS IN 1 % AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



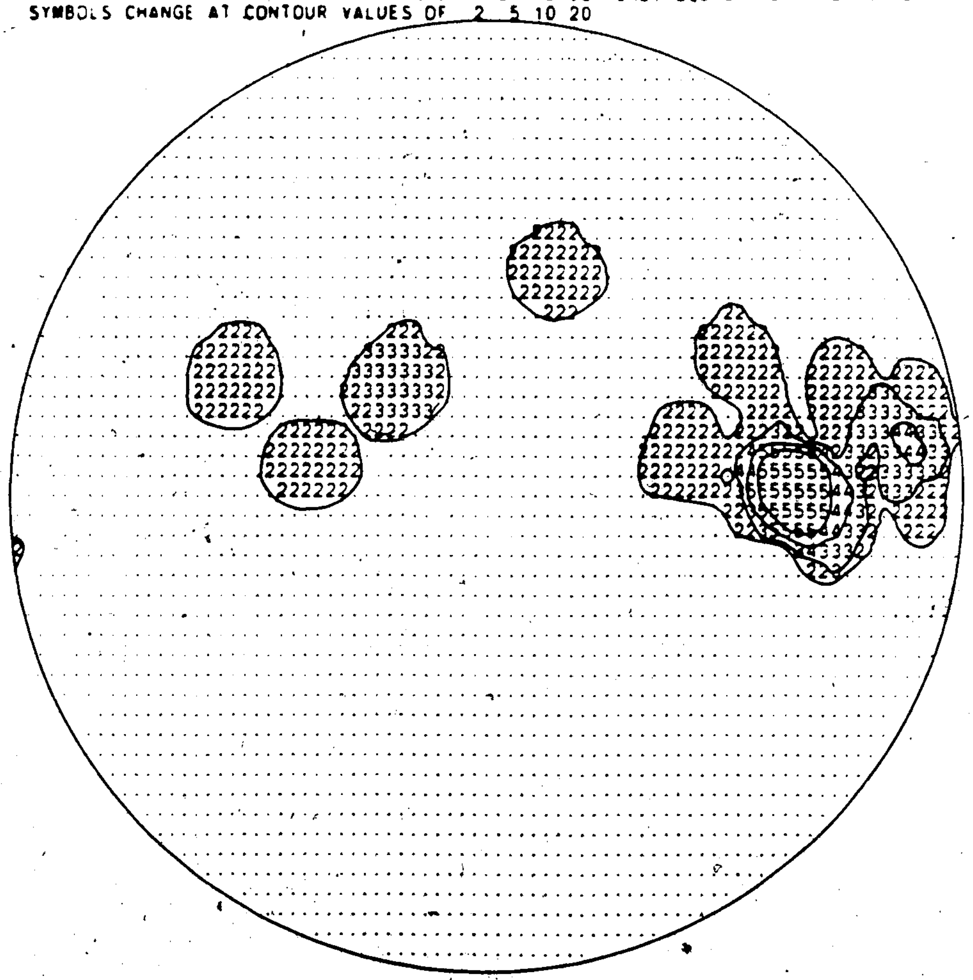
TREND	PLUNGE	EVAL	EVAL/N
107	21	6.9396	0.8675
330	63	0.9071	0.1134
204	17	0.1533	0.0192

STRUCTURAL DOMAIN 10 RUNDLE
PERCENTAGES OF 20 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



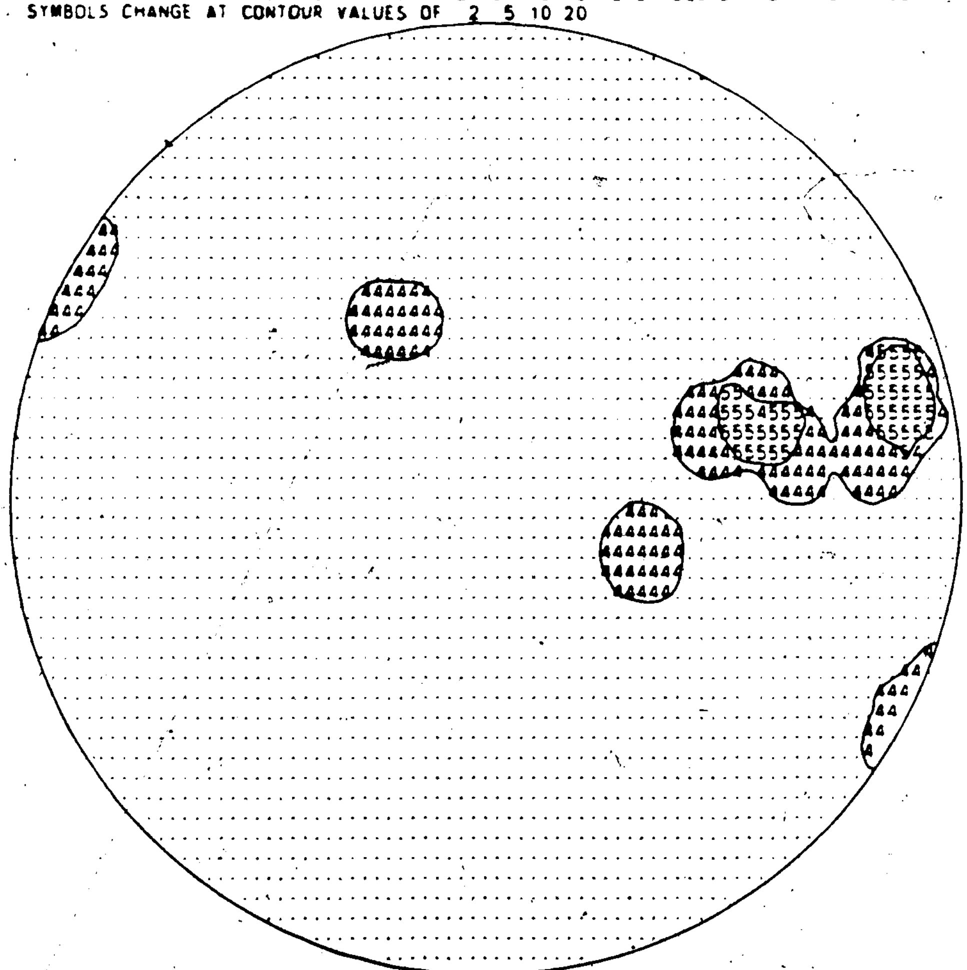
TREND	PLUNGE	EVAL	EVAL/N
97	14	15.6347	0.7817
319	71	4.1223	0.2061
190	12	0.2429	0.0121

STRUCTURAL DOMAIN 11 RUNDLE
PERCENTAGES OF 21 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



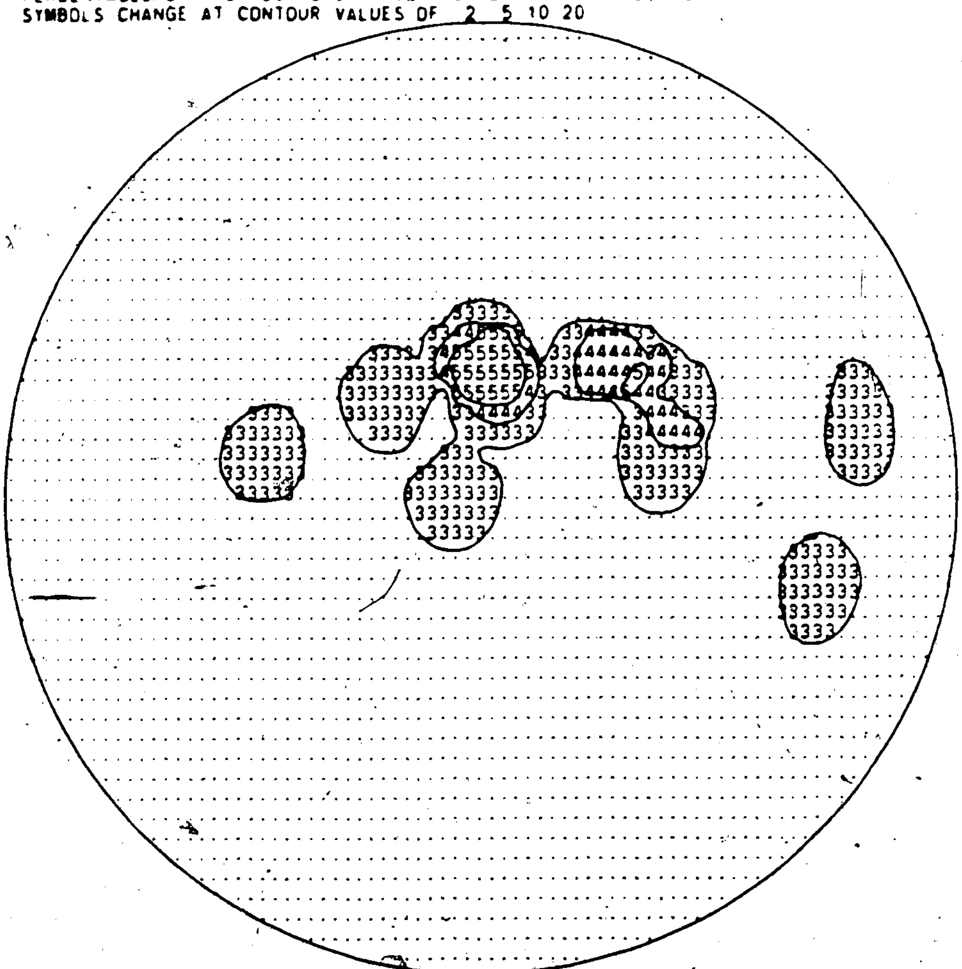
TREND	PLUNGE	EVAL	EVAL/N
83	35	15.7373	0.7494
292	50	4.8068	0.2289
185	17	0.4559	0.0217

STRUCTURAL DOMAIN 12 CRET
PERCENTAGES OF 9 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



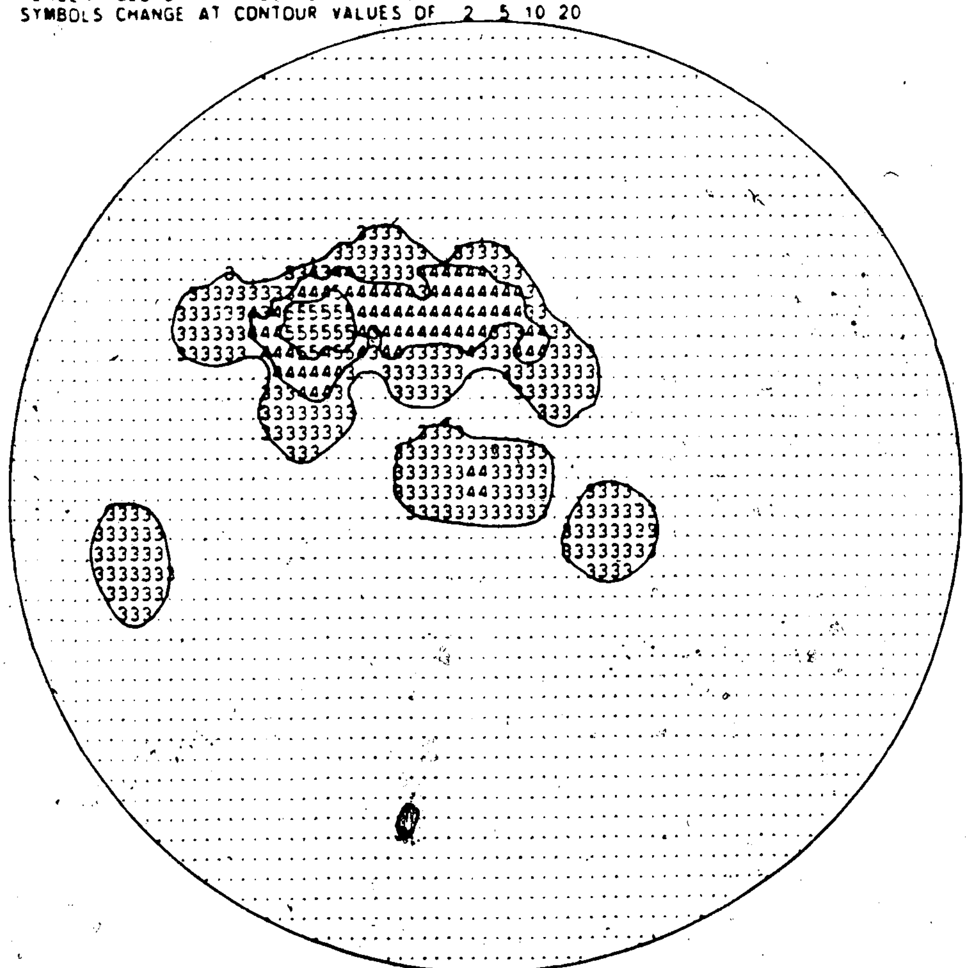
TREND	PLUNGE	EVAL	EVAL/N
84	31	6.7577	0.7509
306	52	1.7926	0.1992
187	21	0.4496	0.0500

STRUCTURAL DOMAIN 13 CRET
PERCENTAGES OF 13 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



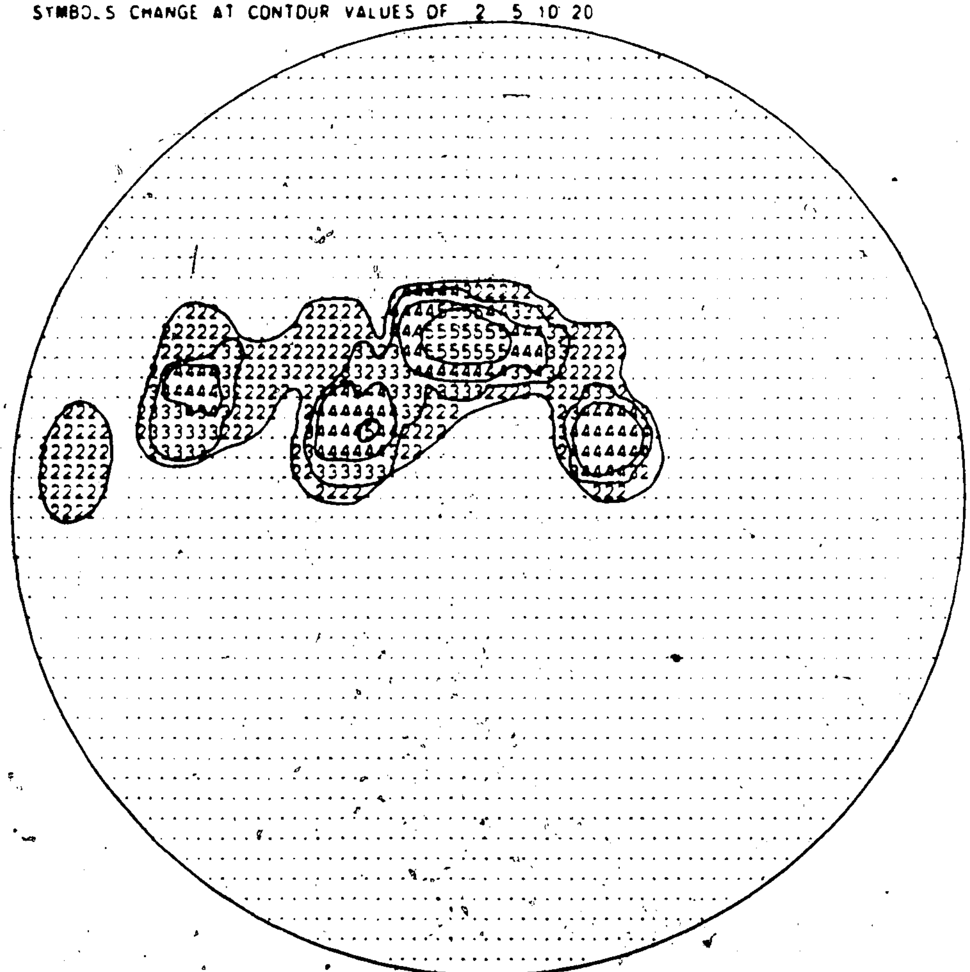
TREND	PLUNGE	EVAL	EVAL/N
37	70	10.1184	0.7783
277	10	2.5642	0.1972
183	17	0.3174	0.0244

STRUCTURAL DOMAIN 14 CRET.
PERCENTAGES OF 17 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



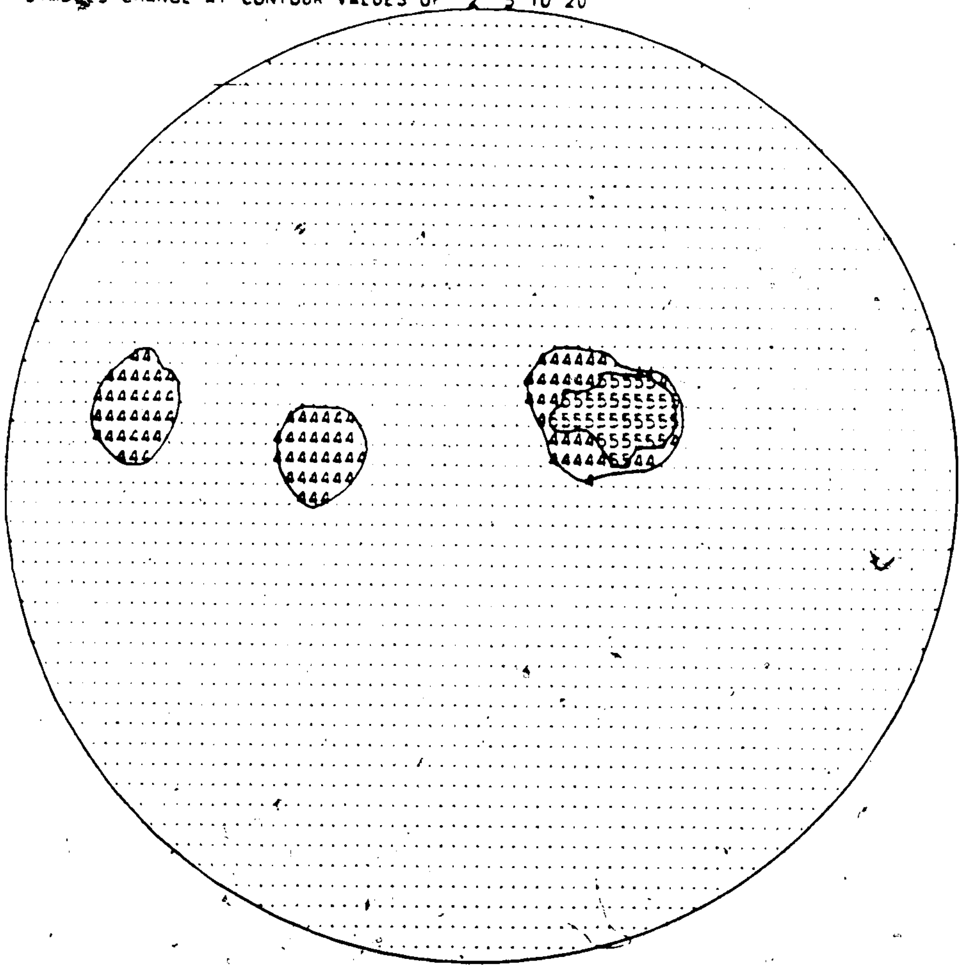
TREND	PLUNGE	EVAL	EVAL/N
326	61	14.1486	0.8323
96	20	2.0313	0.1195
194	20	0.8201	0.0482

STRUCTURAL DOMAIN 15 CRET.
PERCENTAGES OF 23 POINTS IN 1 % AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



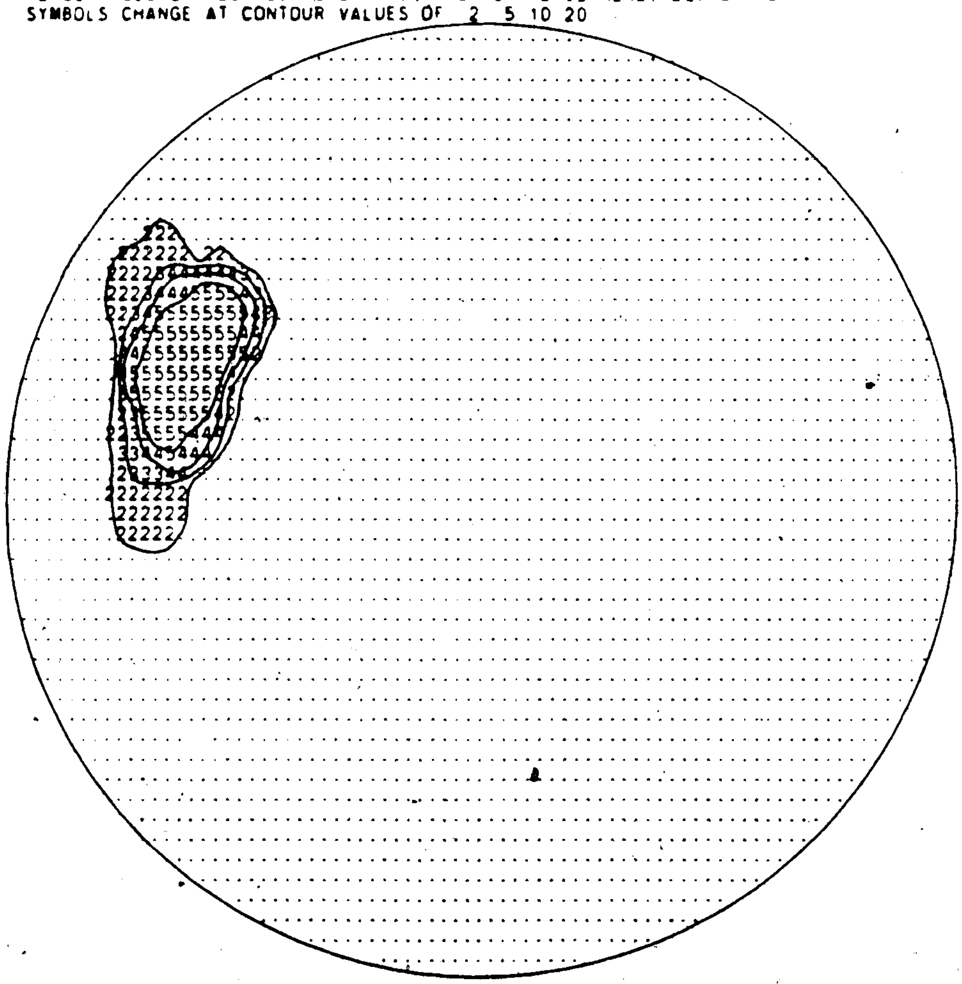
TREND	PLUNGE	EVAL	EVAL/N
325	65	18.7946	0.8172
87	14	3.8539	0.1676
183	20	0.3514	0.0153

STRUCTURAL DOMAIN 16 CRET.
PERCENTAGES OF 6 POINTS IN 1.% AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



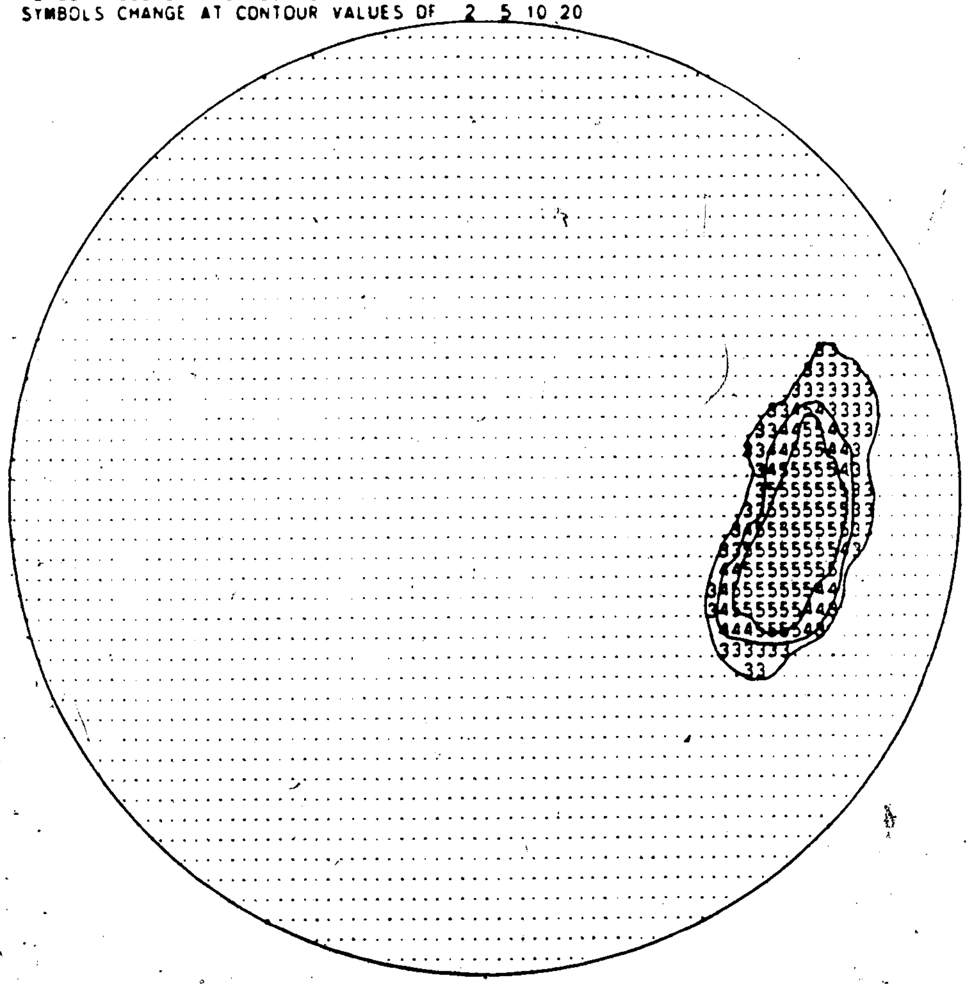
TREND	PLUNGE	EVAL	EVAL/N
42	75	4.5044	0.7507
272	10	1.4706	0.2451
180	11	0.0249	0.0042

KINEMATIC STUDY BEDDING DOMAIN 1
PERCENTAGES OF 29 POINTS IN 1.% AREA OF HEMISPHERE, EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



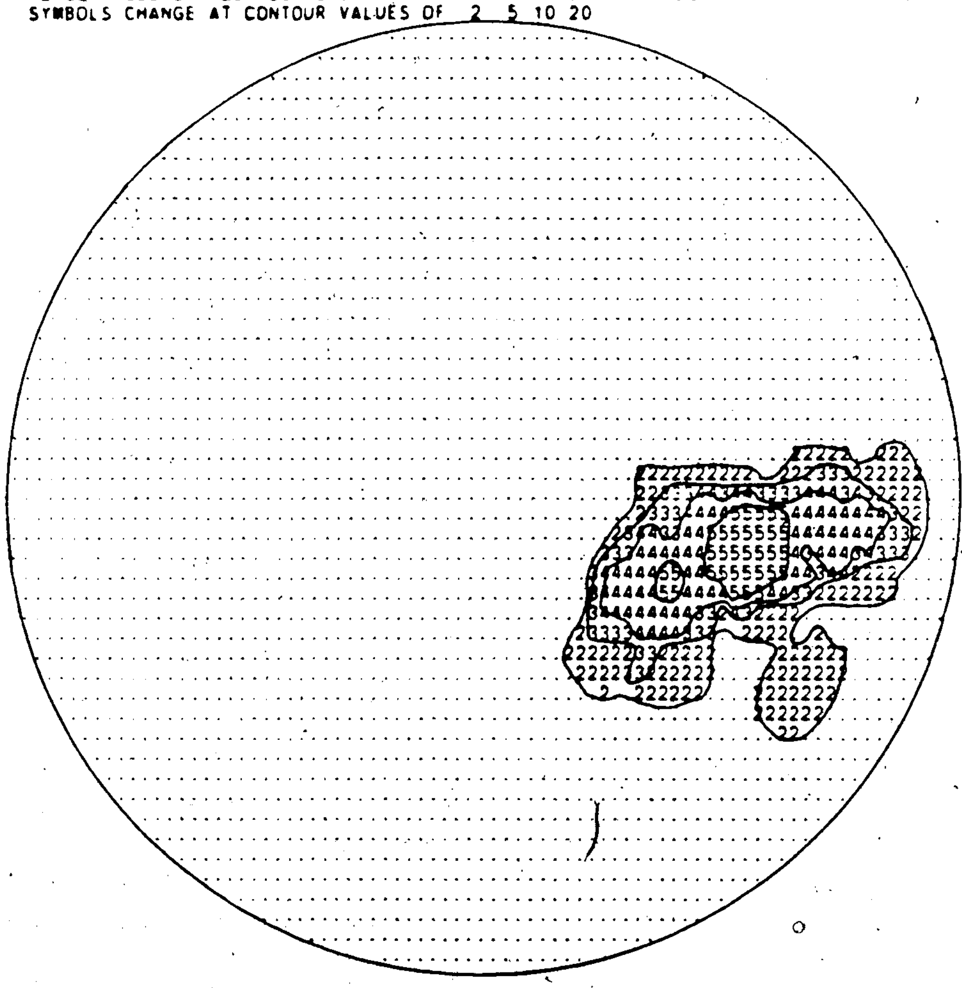
TREND	PLUNGE	EVAL	EVAL/N
294	31	28.4611	0.9814
197	12	0.4151	0.0143
88	57	0.1237	0.0043

KINEMATIC STUDY BEDDING DOMAIN 2
PERCENTAGES OF 15 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



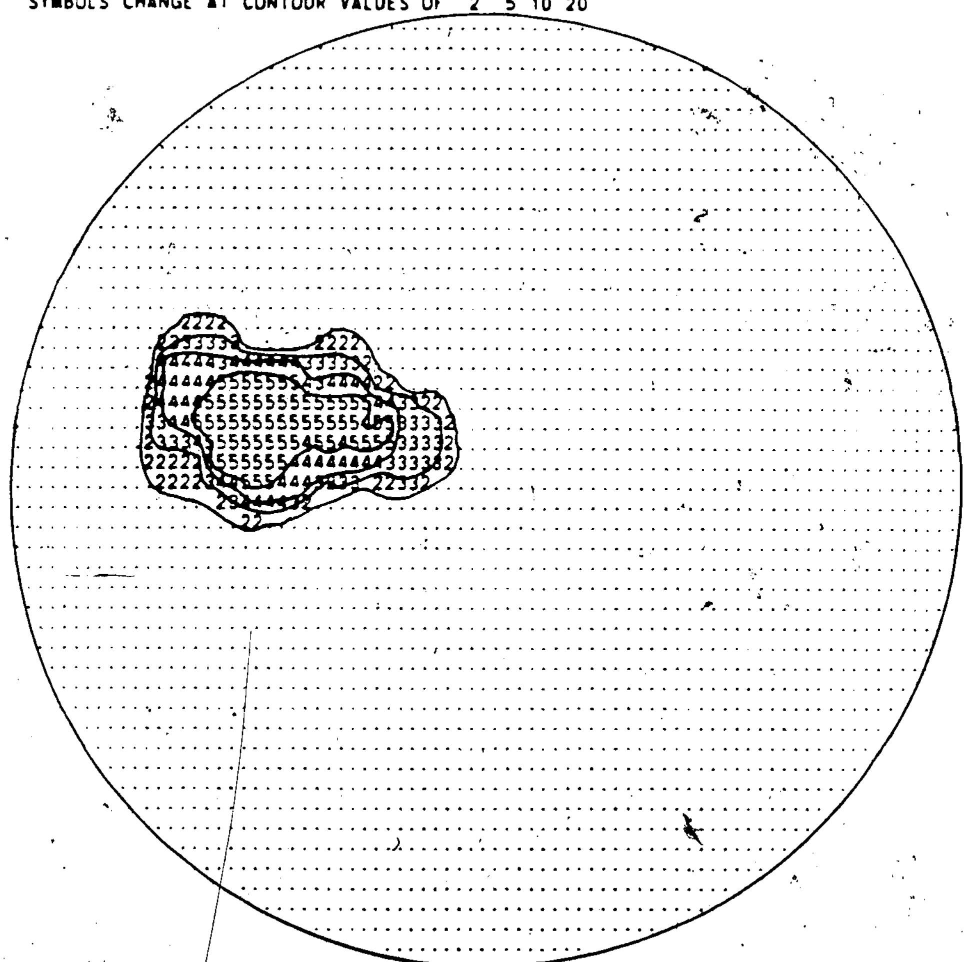
TREND	PLUNGE	EVAL	EVAL/N
98	33	14.5586	0.9706
197	12	0.3951	0.0263
304	54	0.0462	0.0031

KINEMATIC STUDY BEDDING DOMAIN 3
PERCENTAGES OF 26 POINTS IN 1.% AREA OF HEMISPHERE EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



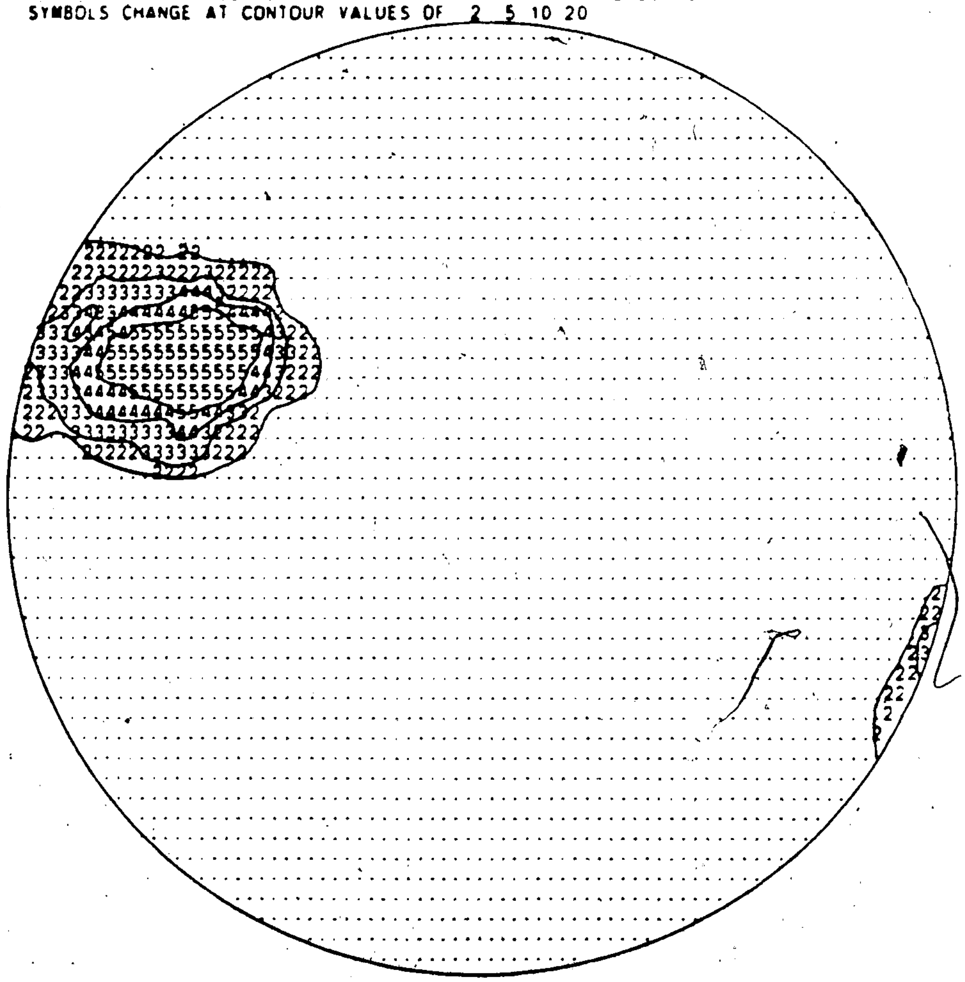
TREND	PLUNGE	EVAL	EVAL/N
106	43	24.1450	0.9287
249	41	1.4814	0.0570
357	19	0.3735	0.0144

KINEMATIC STUDY BEDDING DOMAIN 4
PERCENTAGES OF 24 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



TREND	PLUNGE	EVAL	EVAL/N
286	52	22.9280	0.9553
97	38	0.9278	0.0387
190	4	0.1440	0.0060

KINEMATIC STUDY BEDDING DOMAIN 5
PERCENTAGES OF 32 POINTS IN 1.% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20



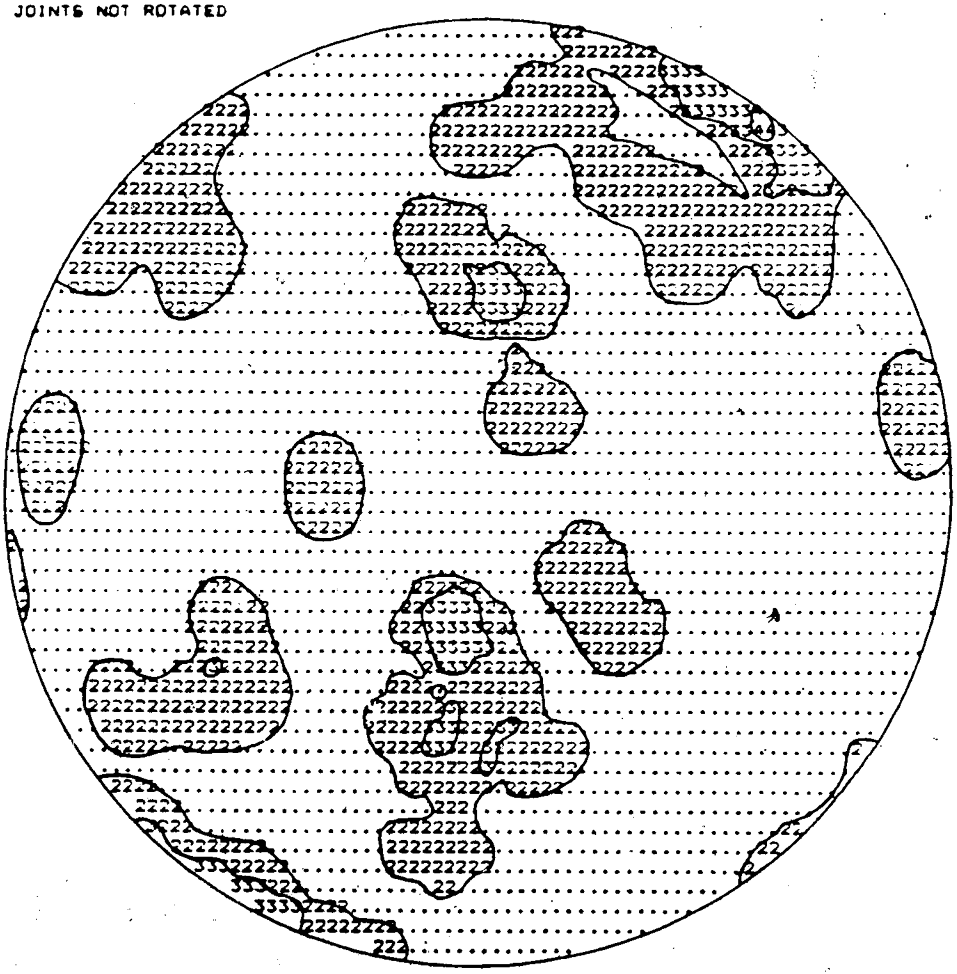
TREND	PLUNGE	EVAL	EVAL/N
293	28	30.6033	0.9564
88	59	1.1767	0.0368
197	11	0.2199	0.0069

F. Appendix 6

Joint Orientation Diagrams

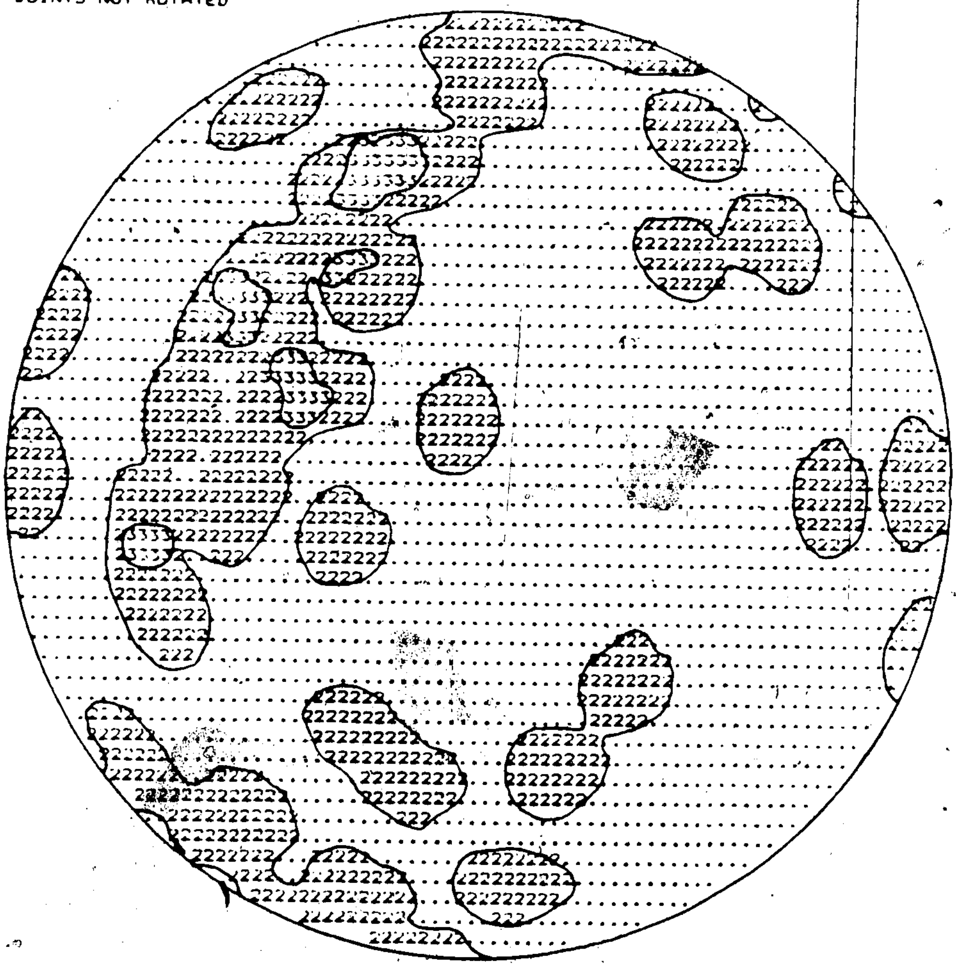
These high density pi-diagrams illustrate the jointing in the slope stability domains both before and after bedding has been rotated to horizontal. Rotation of the joints to the horizontal done by first rotating the fold axis to horizontal and then the bedding.

1KINEMATIC DOMAIN 1 JOINTS
PERCENTAGES OF 42 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS NOT ROTATED



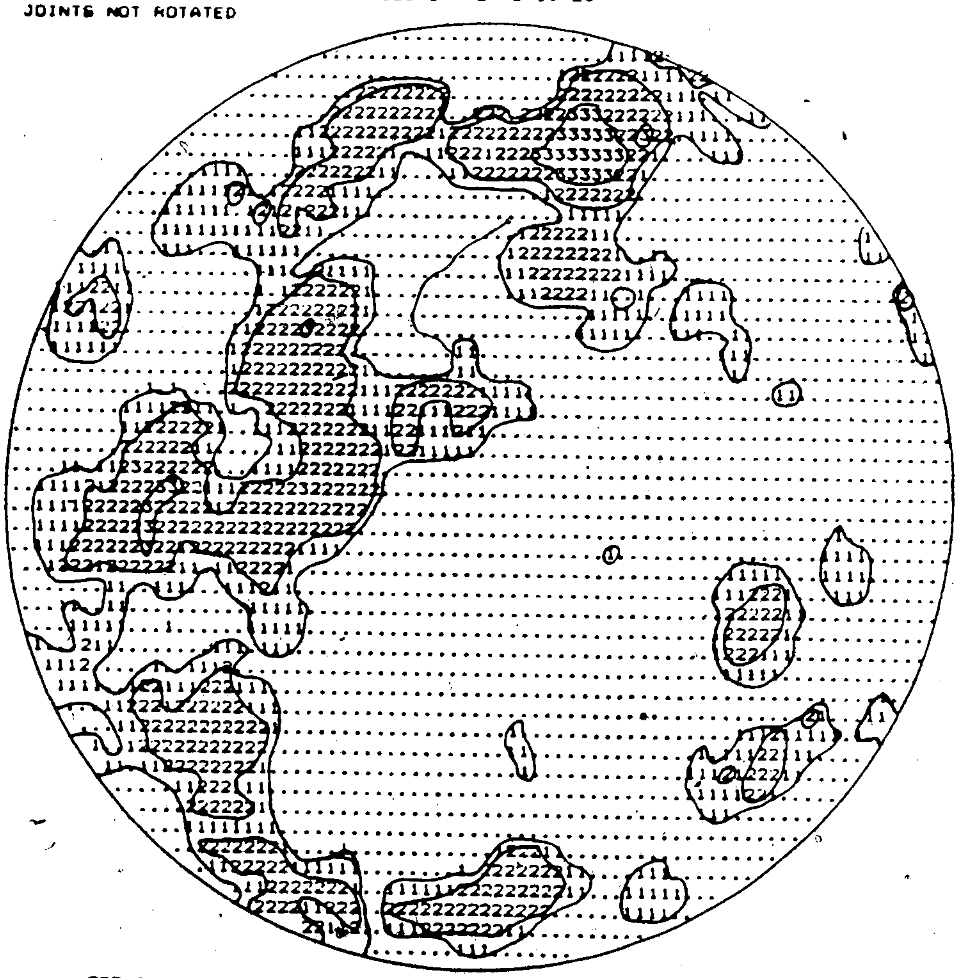
TREND	PLUNGE	EIGENVALUE/N
209.4	4.7	.4870
14.5	85.1	.3211
119.3	1.2	.1919

KINEMATIC DOMAIN 2 JOINTS
PERCENTAGES OF 44 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS NOT ROTATED



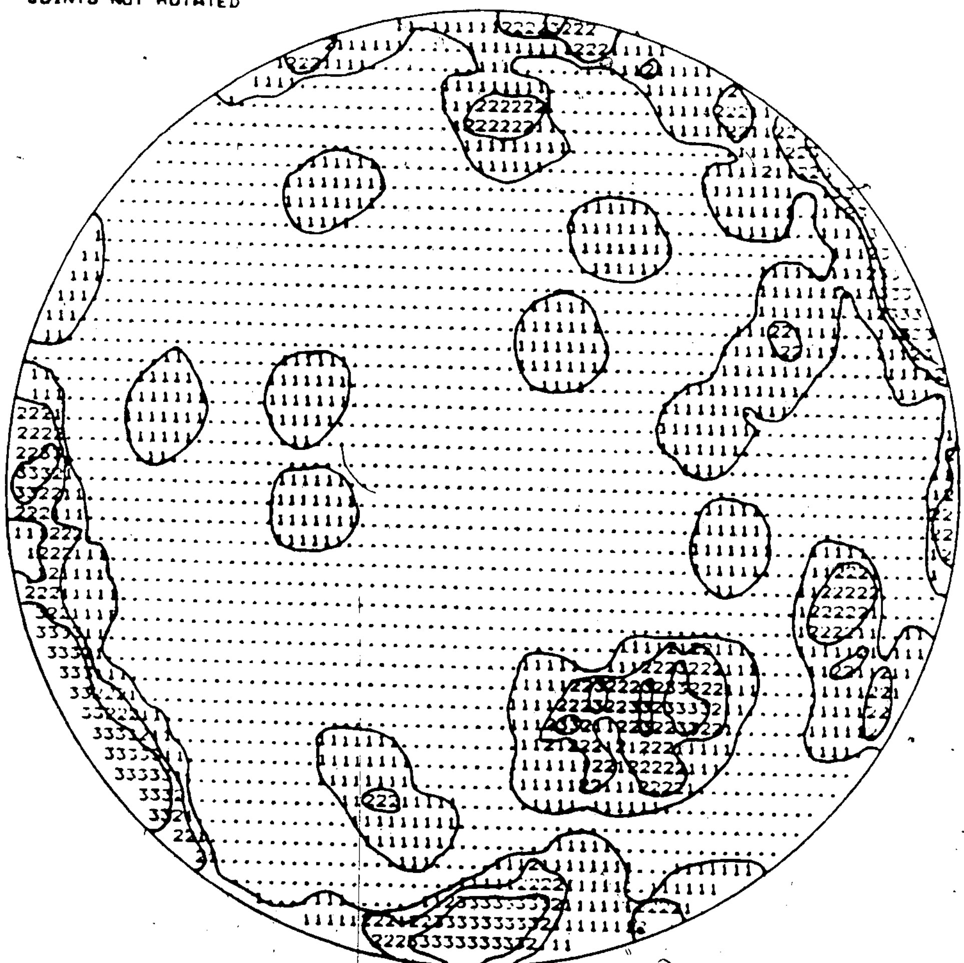
TREND	PLUNGE	EIGENVALUE/N
30[illegible]	41.[illegible]	.4884
20[illegible]	[illegible].7	.[illegible]
11[illegible].4	48.2	.14[illegible]

1KINEMATIC DOMAIN 3 JOINTS
PERCENTAGES OF 139 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS NOT ROTATED



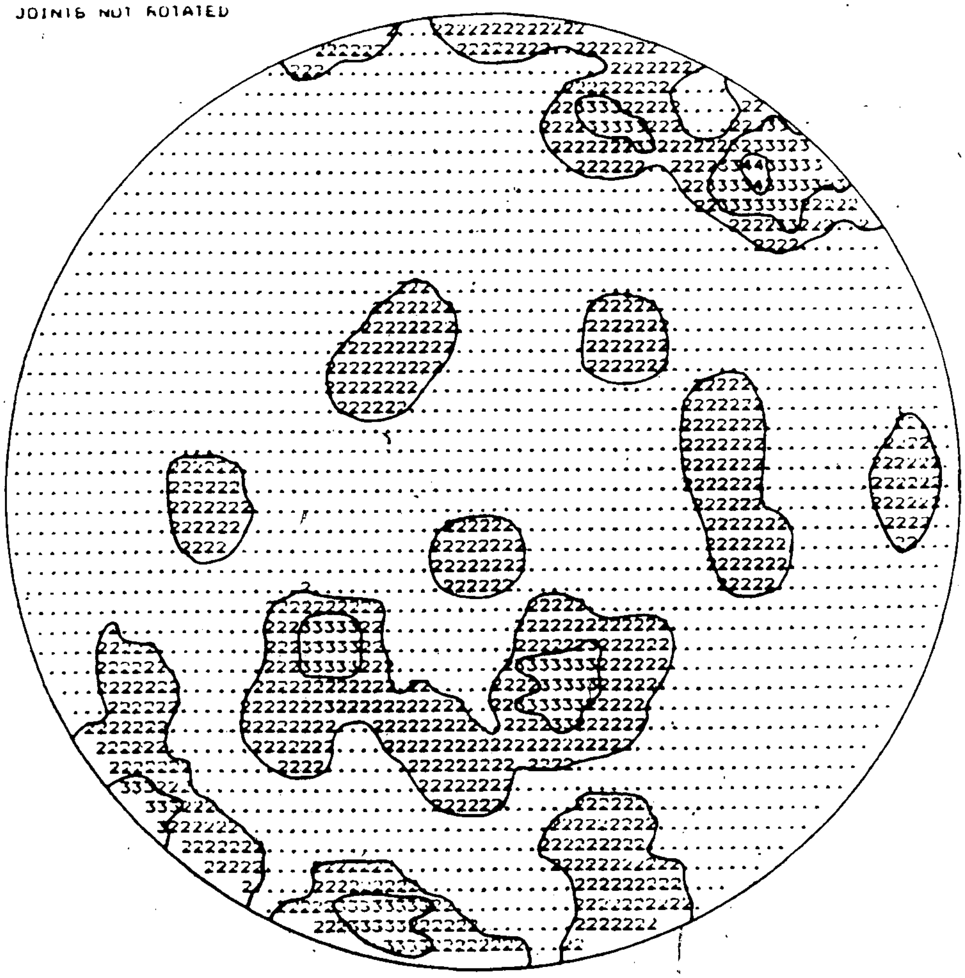
TREND	PLUNGE	EIGENVALUE/N
328.3	38.2	.4250
227.3	13.7	.3862
121.3	48.5	.1889

1KINEMATIC DOMAIN 4 JOINTS
PERCENTAGES OF 52 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS NOT ROTATED



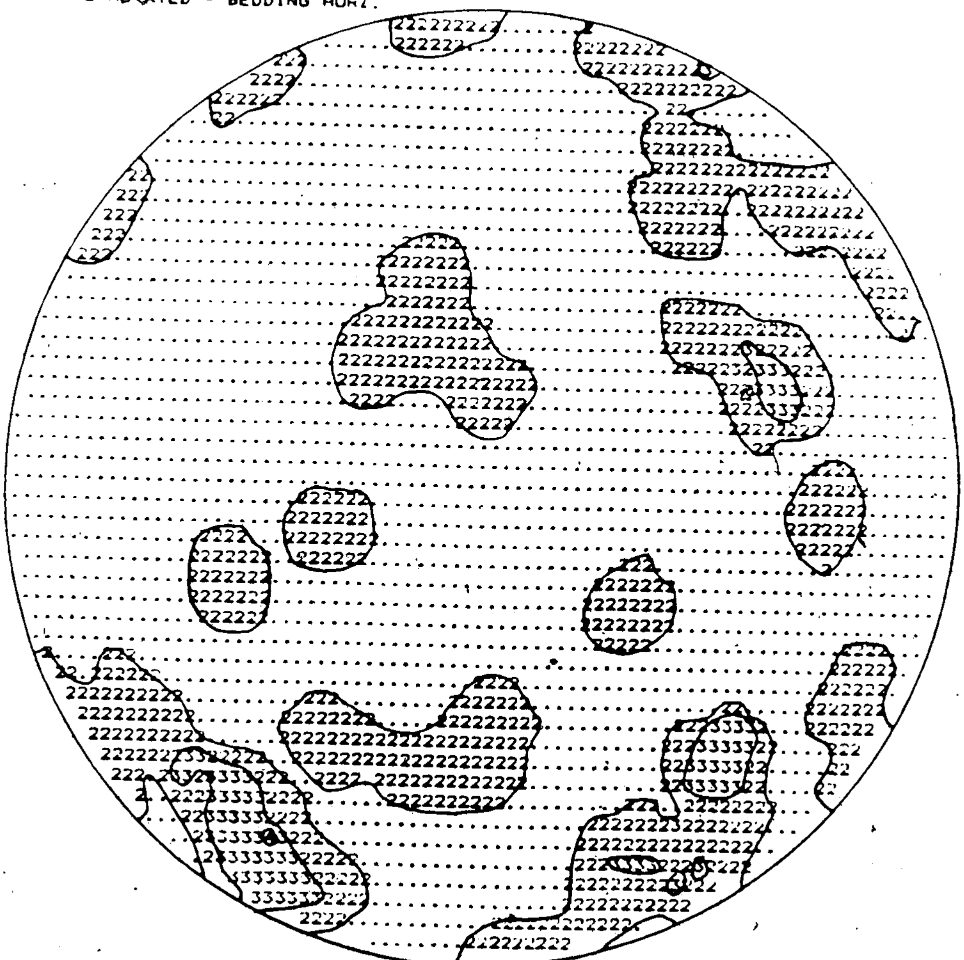
TREND	PLUNGE	EIGENVALUE/N
40.7	1.1	.4612
131.1	19.8	.3845
307.8	70.2	.1543

KINEMATIC DOMAIN 5 JOINTS
PERCENTAGES OF 43 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS NOT ROTATED



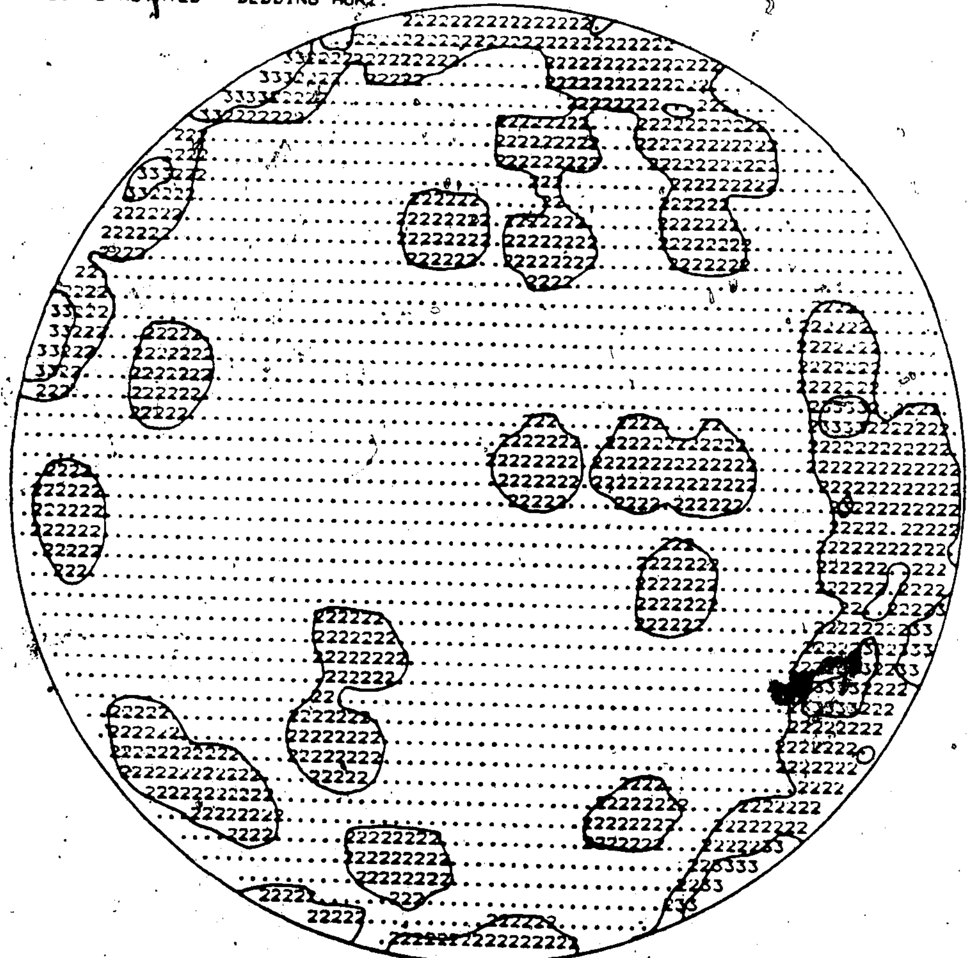
TREND	PLUNGE	EIGENVALUE/N
204.0	18.0	.5421
79.4	60.2	.3138
301.9	22.9	.1441

KINEMATIC DOMAIN 1 JOINTS ROTATED: 204. 0. -59.
PERCENTAGES OF 42 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS ROTATED - BEDDING HORZ.



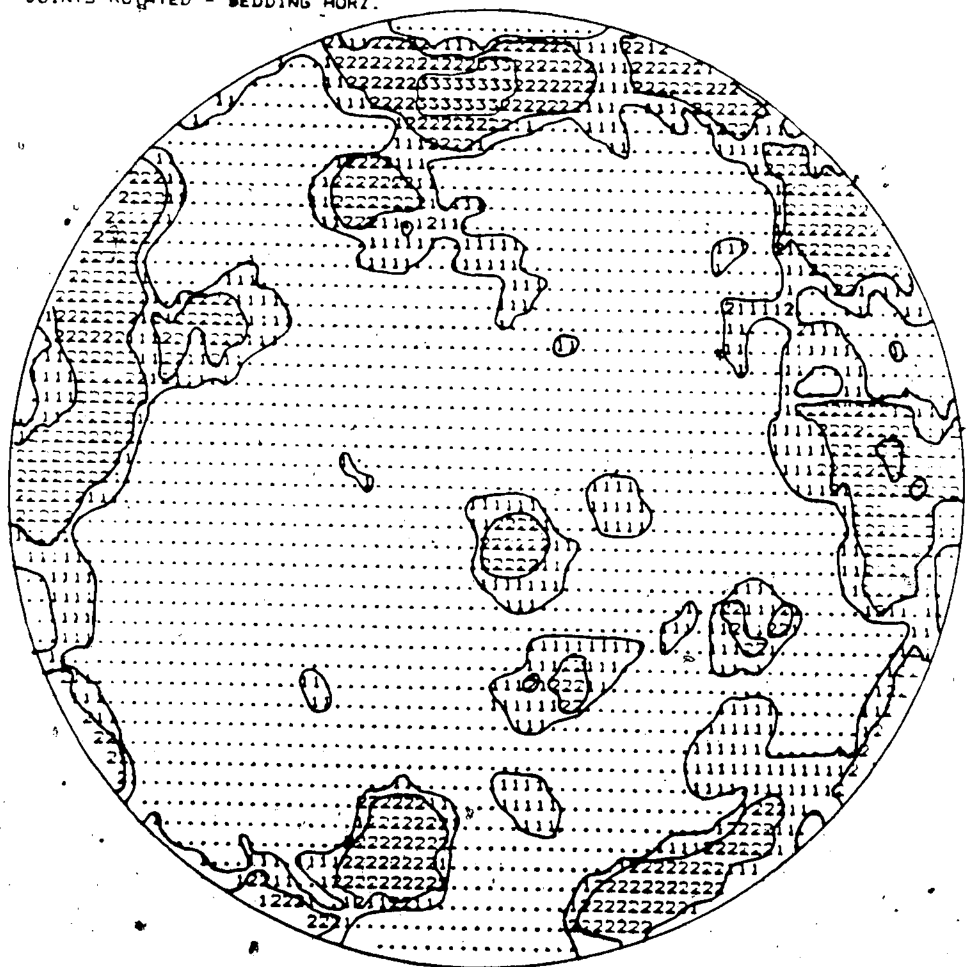
TREND	PLUNGE	EIGENVALUE/N
201.7	9.1	.4870
105.9	32.2	.3211
305.6	56.[illegible]	.1919

KINEMATIC DOMAIN 2 JOINTS . ROTATED: 188. 0. 57.
PERCENTAGES OF 44 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS ROTATED - BEDDING HORZ.



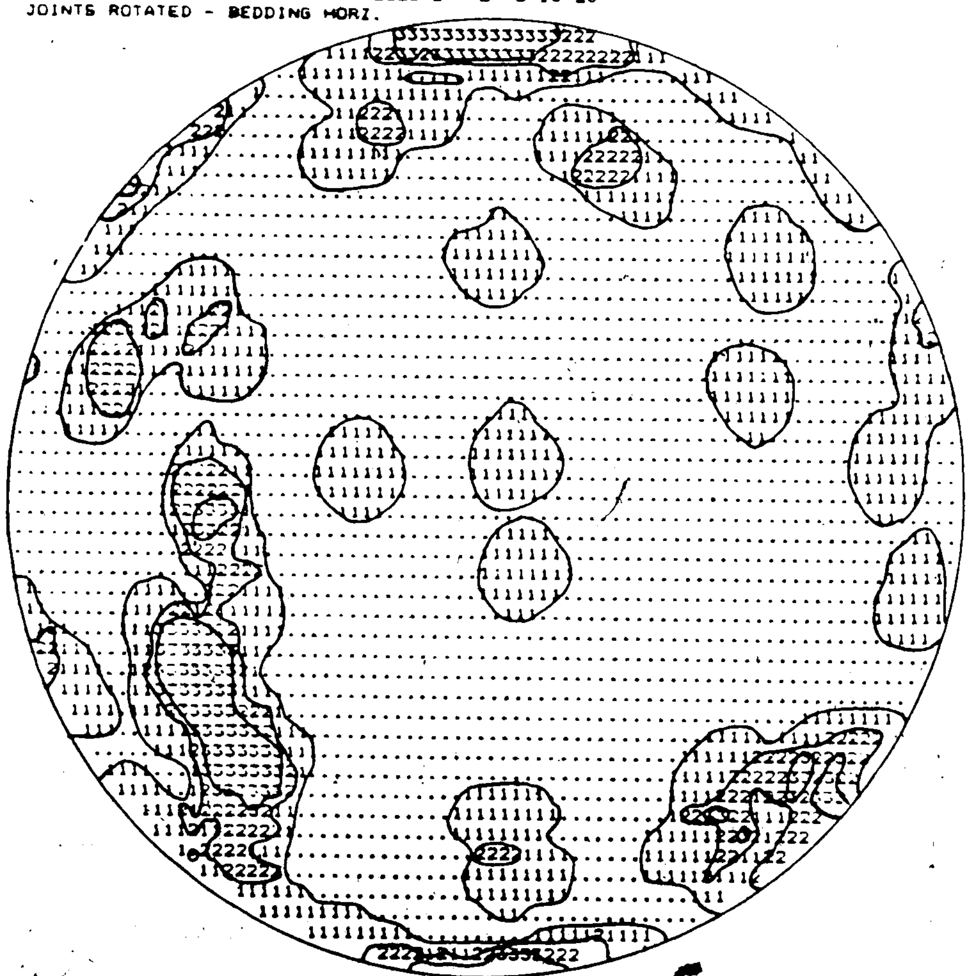
TREND	PLUNGE	EIGENVALUE/N
117.0	10.9	.4?84
24.2	14.4	.3678
243.0	71.8	.1438

KINEMATIC DOMAIN 3 JOINTS   ROTATED: 196.   0.   47.
PERCENTAGES OF 139 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS ROTATED - BEDDING HORZ.



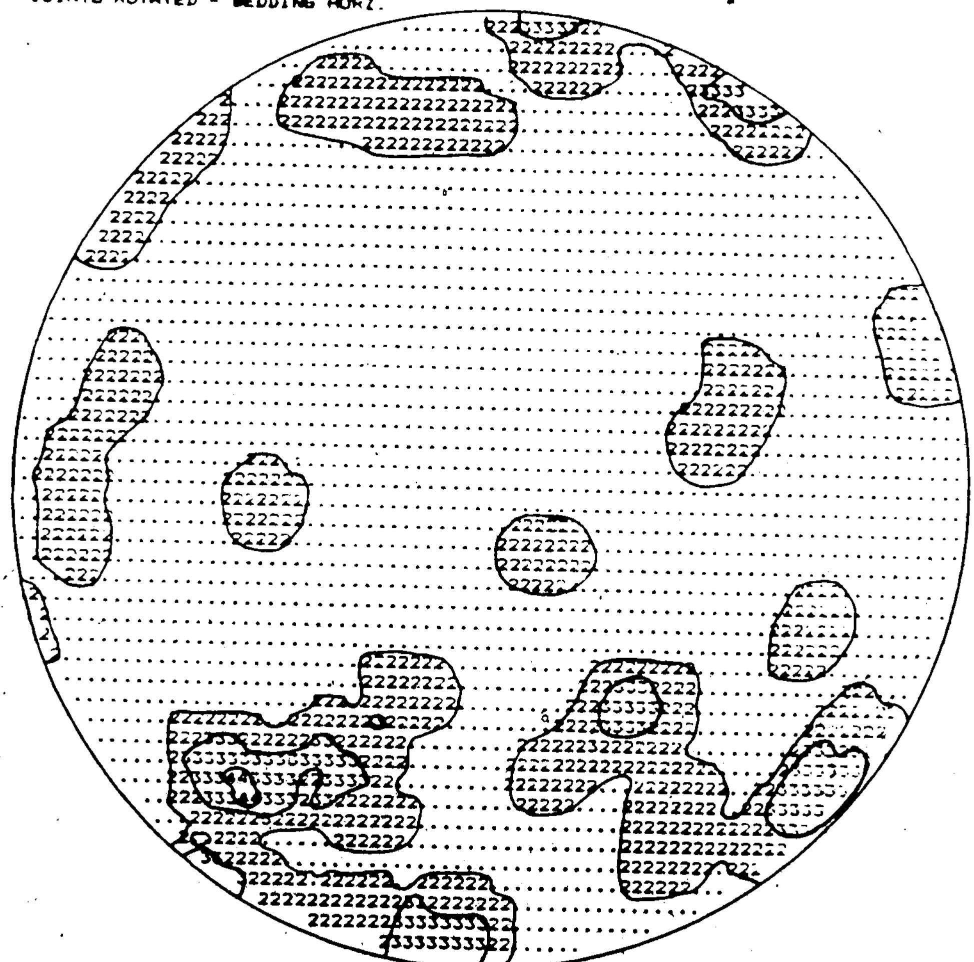
TREND	PLUNGE	EIGENVALUE/N
317.2	1.2	.4250
47.5	13.1	.3862
222.0	76.9	.1889

1KINEMATIC DOMAIN 4 JOINTS ROTATED: 196. 0. -38.
PERCENTAGES OF 52 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS ROTATED - BEDDING HORZ.



TREND	PLUNGE	EIGENVALUE/N
216.3	15.2	.4612
310.2	14.0	.3845
80.8	69.1	.1543

1KINEMATIC DOMAIN 5 JOINTS ROTATED: 193. 0. -62.
PERCENTAGES OF 43 POINTS IN 1% AREA OF HEMISPHERE. EQUAL AREA PROJECTION.
SYMBOLS CHANGE AT CONTOUR VALUES OF 2 5 10 20
JOINTS ROTATED - BEDDING HORZ.



TREND	PLUNGE	EIGENVALUE/N
180.5	19.9	.5421
90.3	.6	.3138
358.6	70.1	.1441

G. Appendix 7

Cross-section Lithologic Symbols

Listed below are the lithologic units represented by the symbols used in Figures 7, 8 and 9.

A = Livingstone Formation

B = Mount Head Formation

C = Etherington Formation

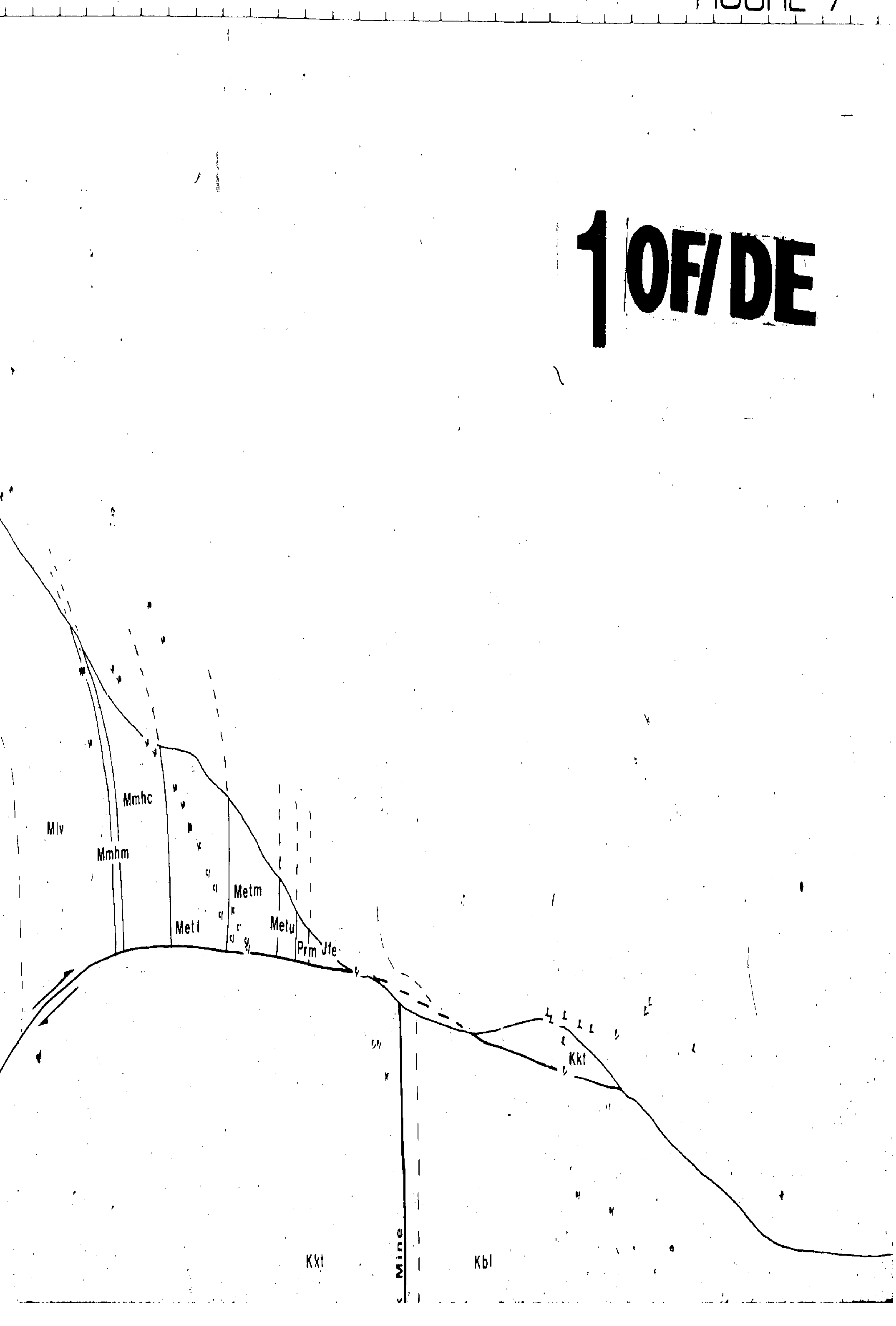
D = Rocky Mountain Formation

E = Fernie Group

F = Kootenay Group

G = Blairmore Group

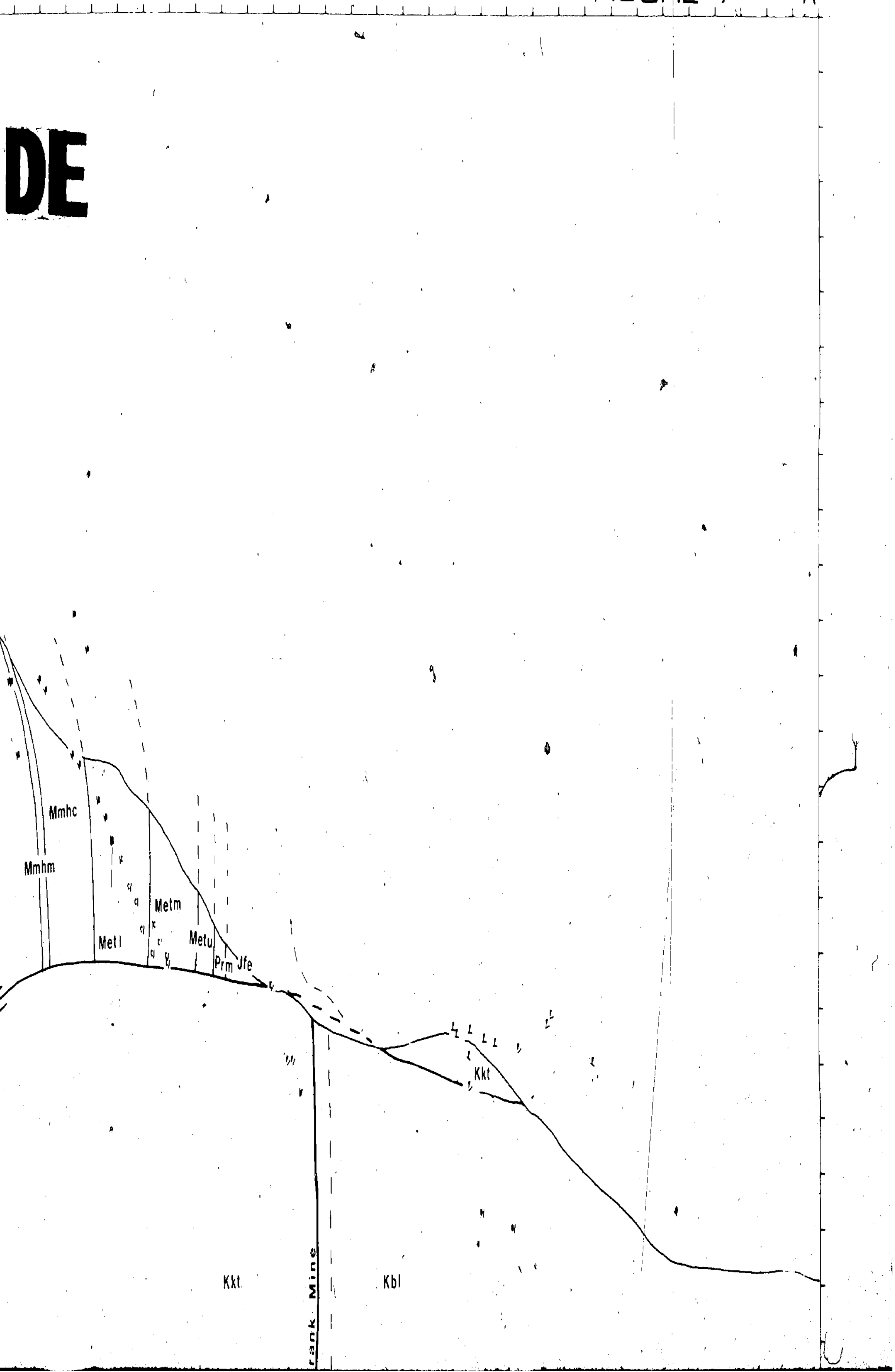
FIGURE 7

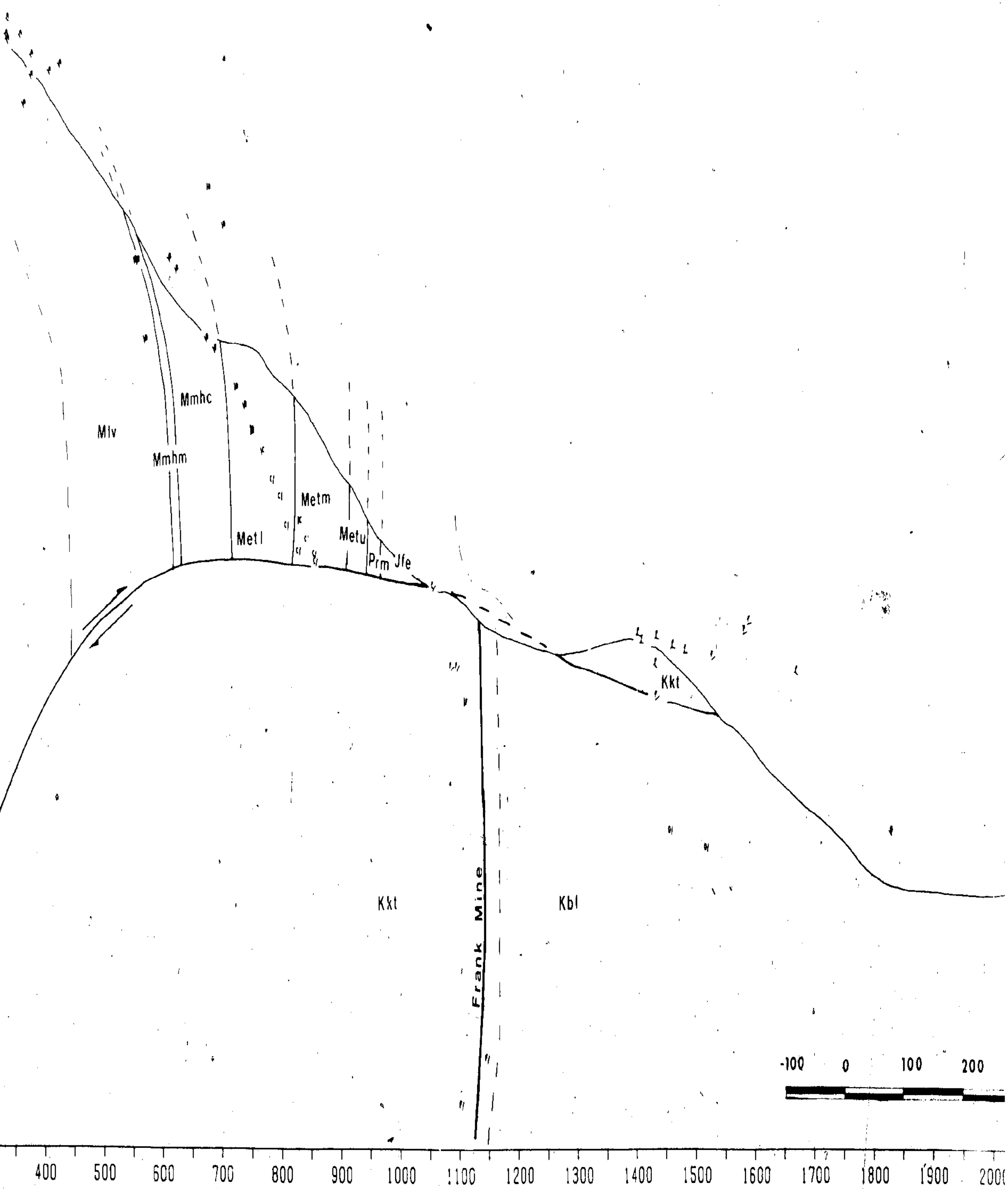


1 OF/DE

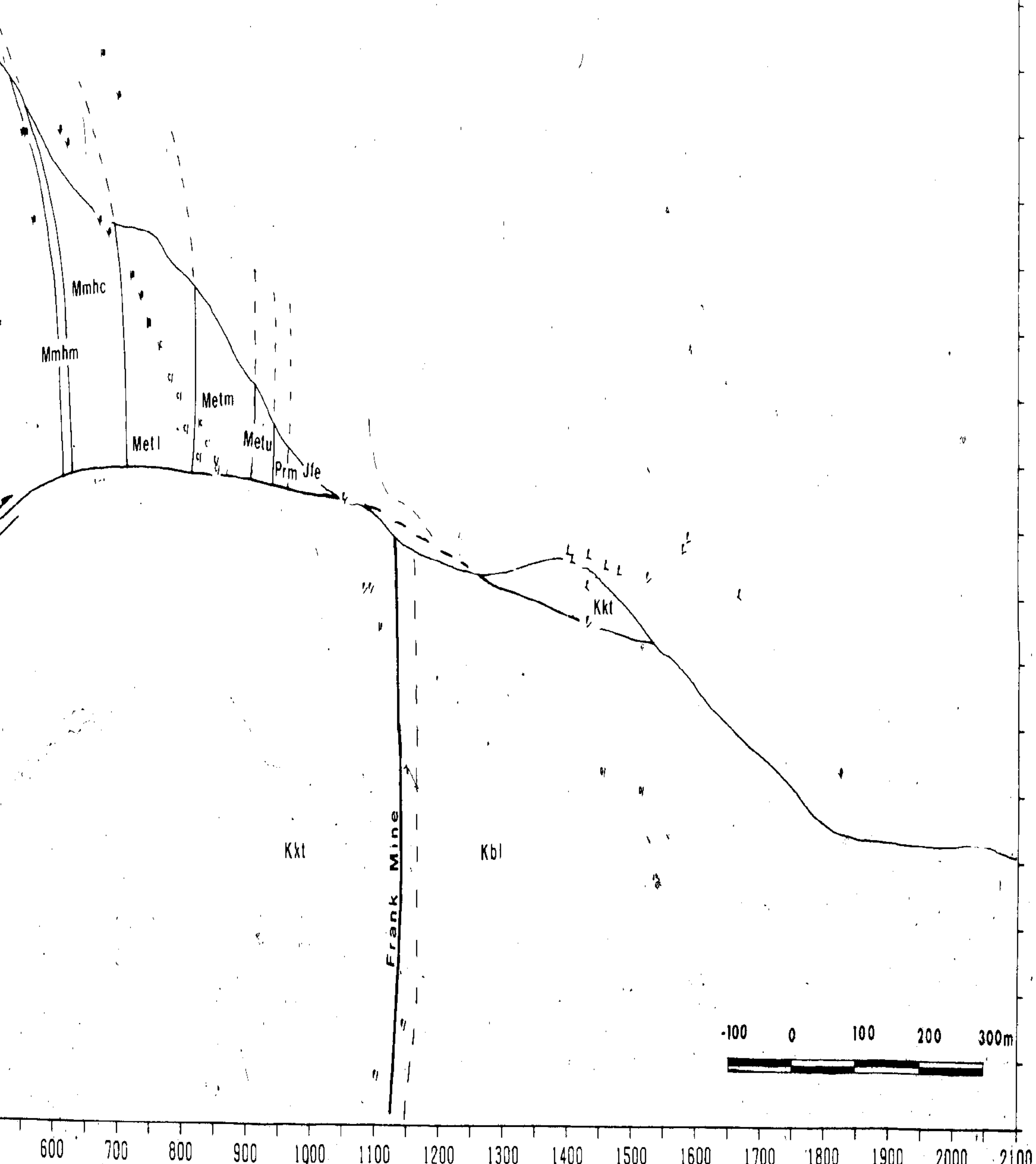
FIGURE 7

DE





CROSS-SECTION A



CROSS-SECTION A

4 OF/DE 4

195 90

FIGURE 8

1 OF/DE

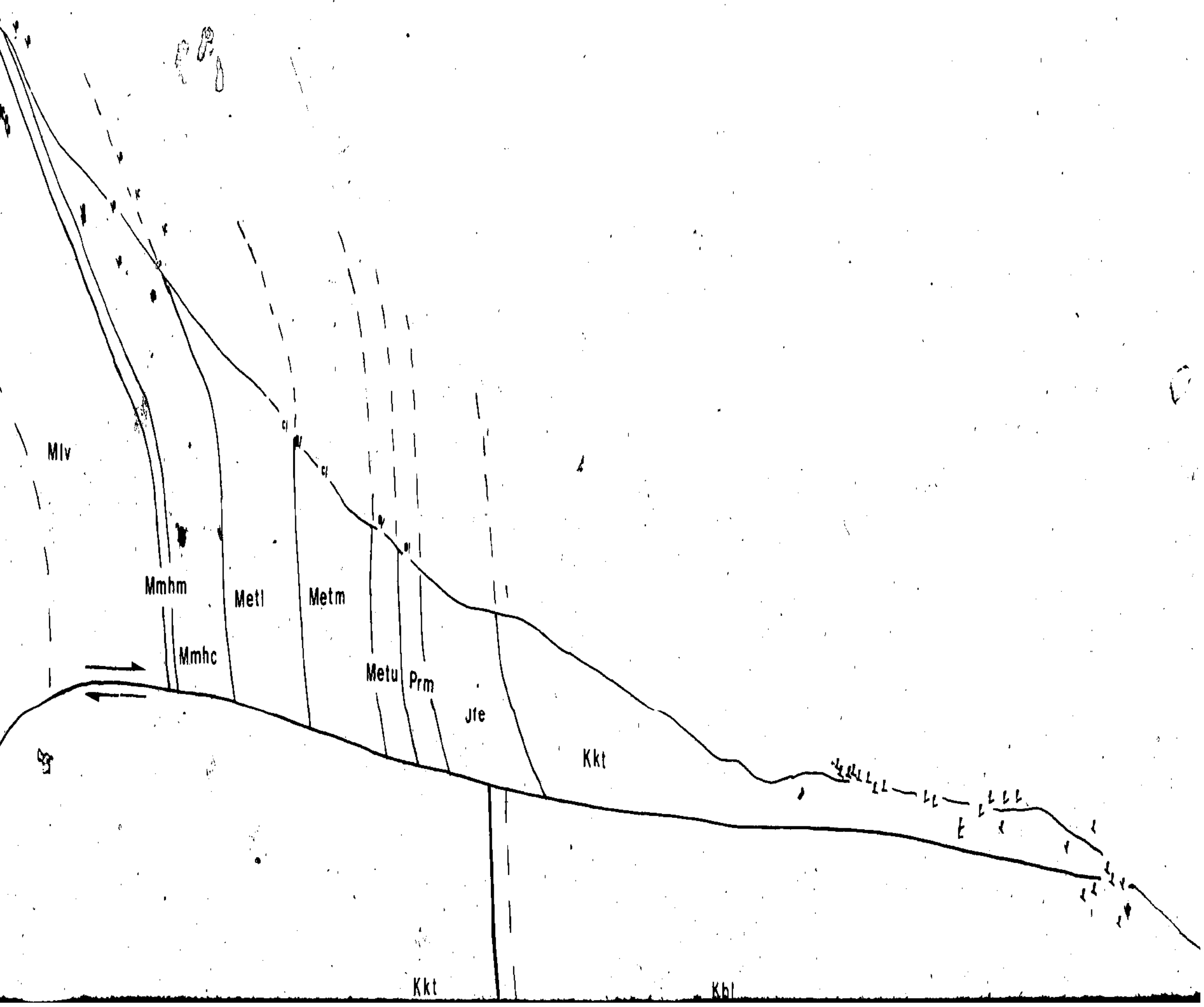
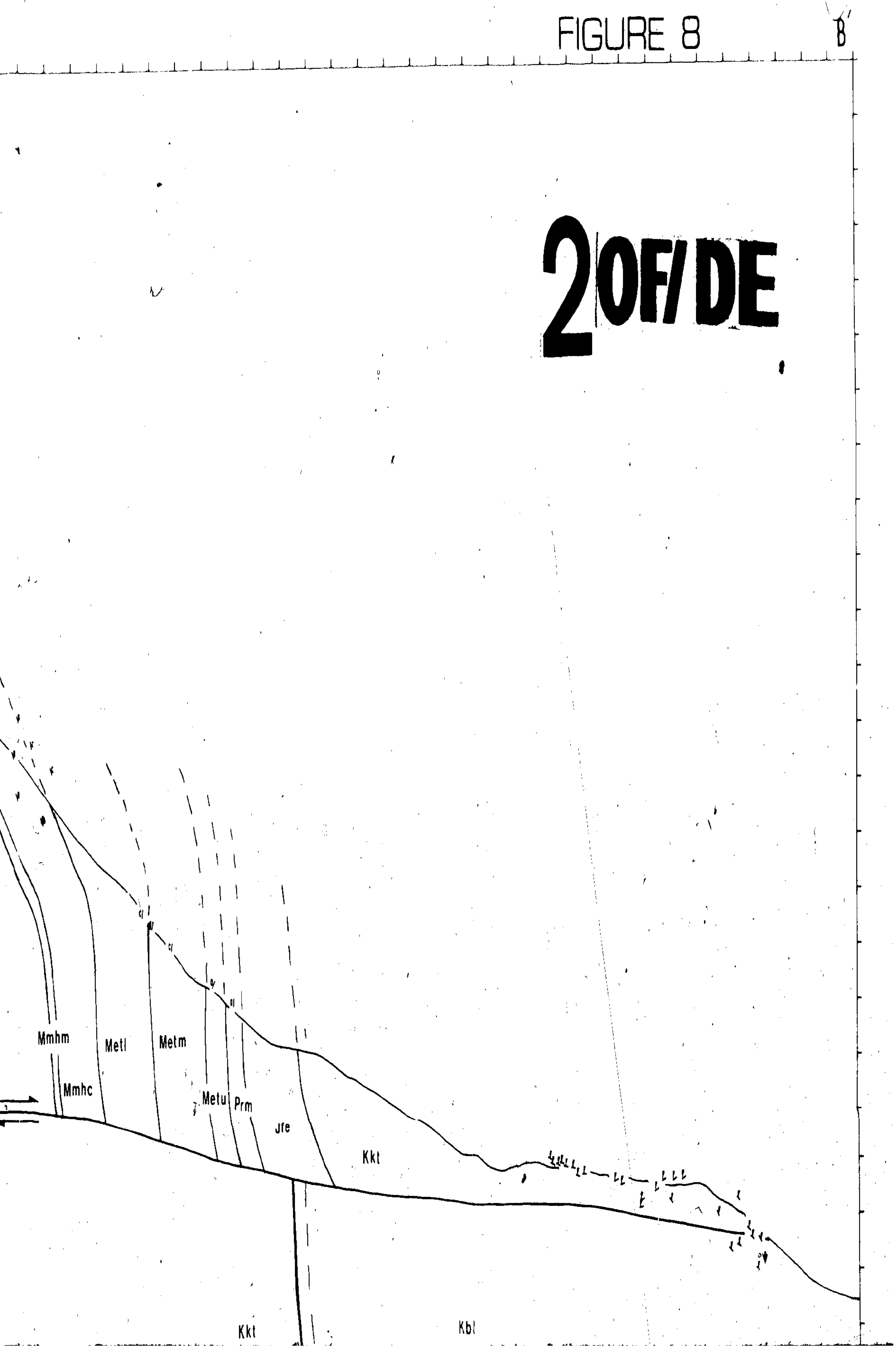
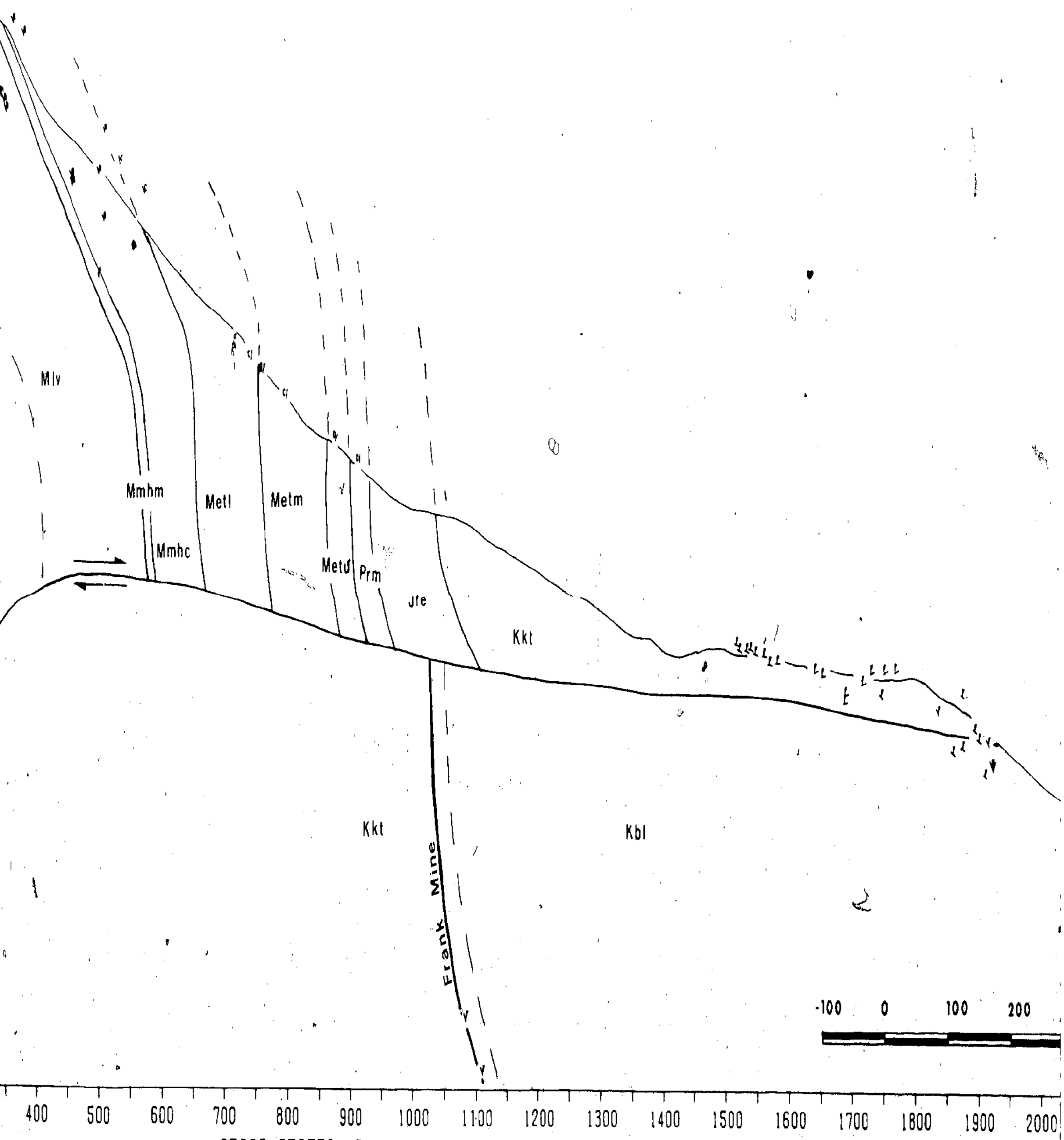


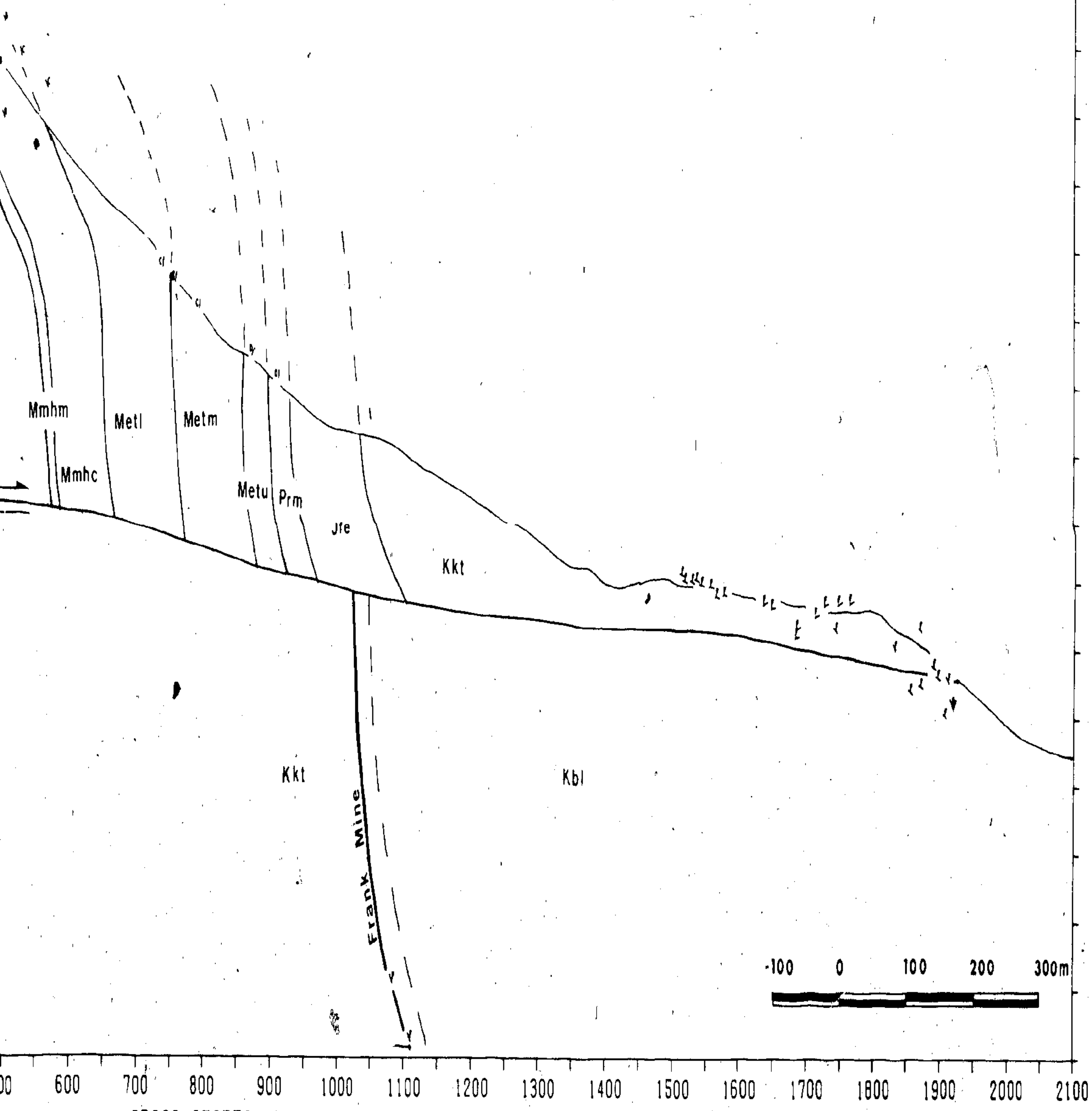
FIGURE 8



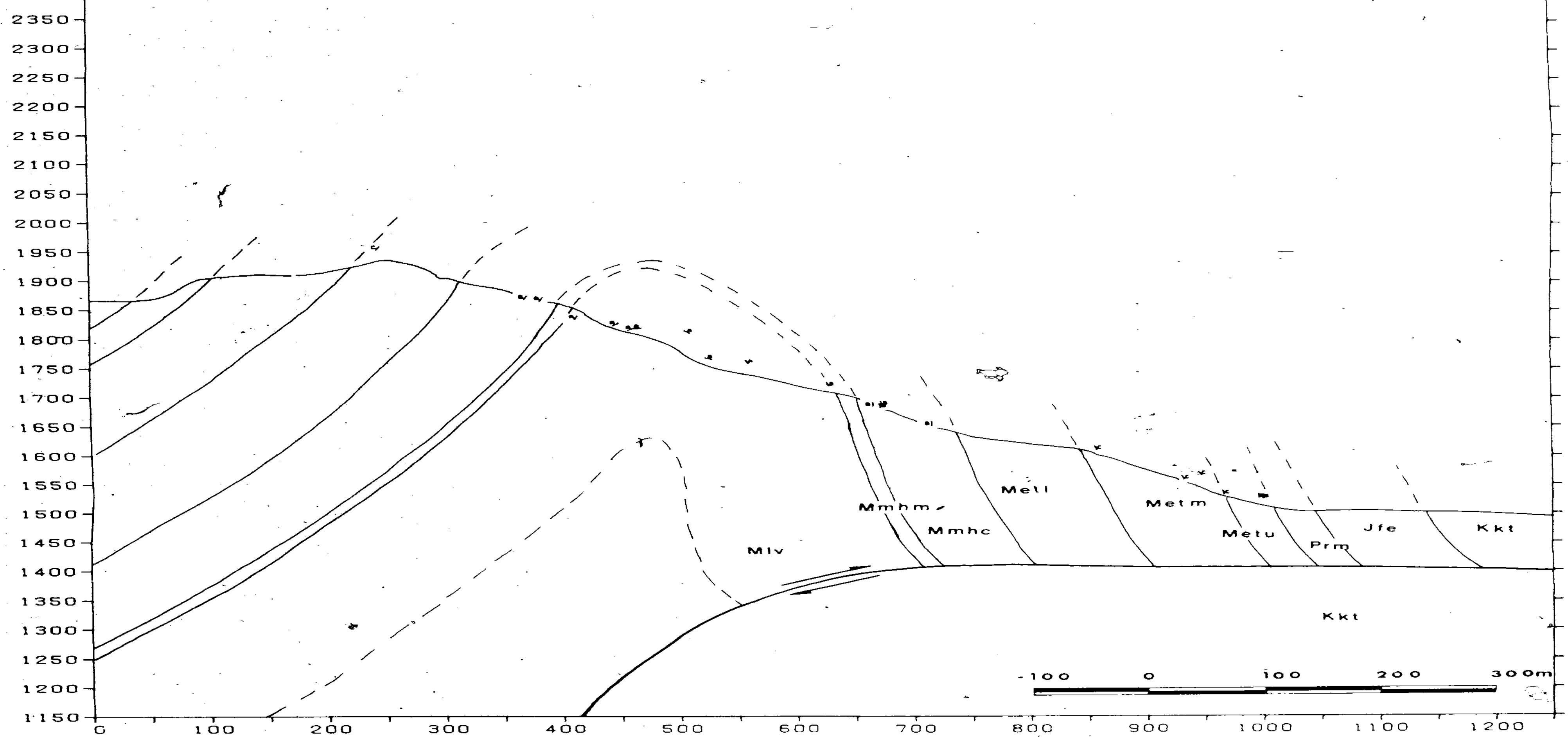
2 OF/DE



CROSS-SECTION B



CROSS-SECTION B



CROSS-SECTION C

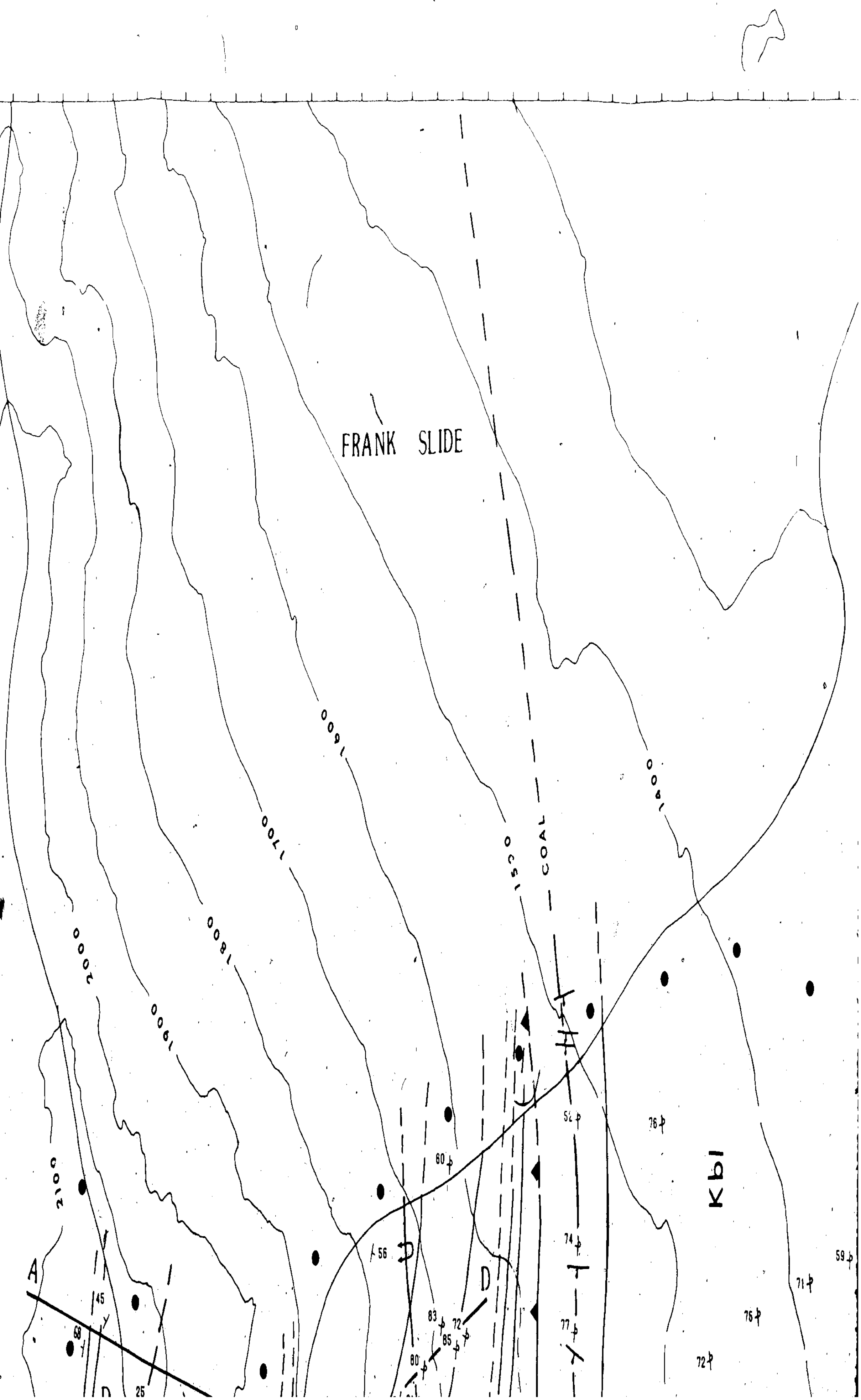
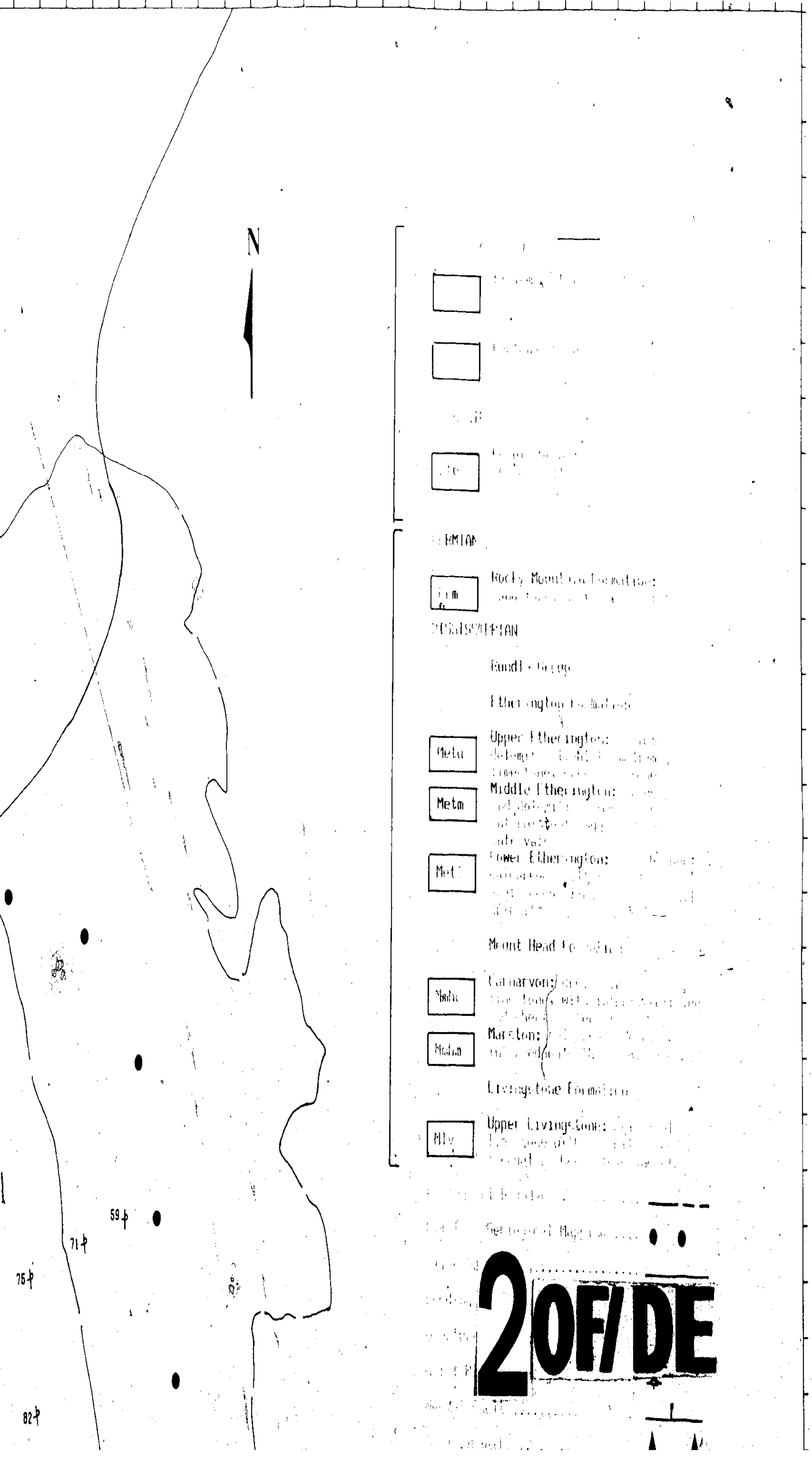
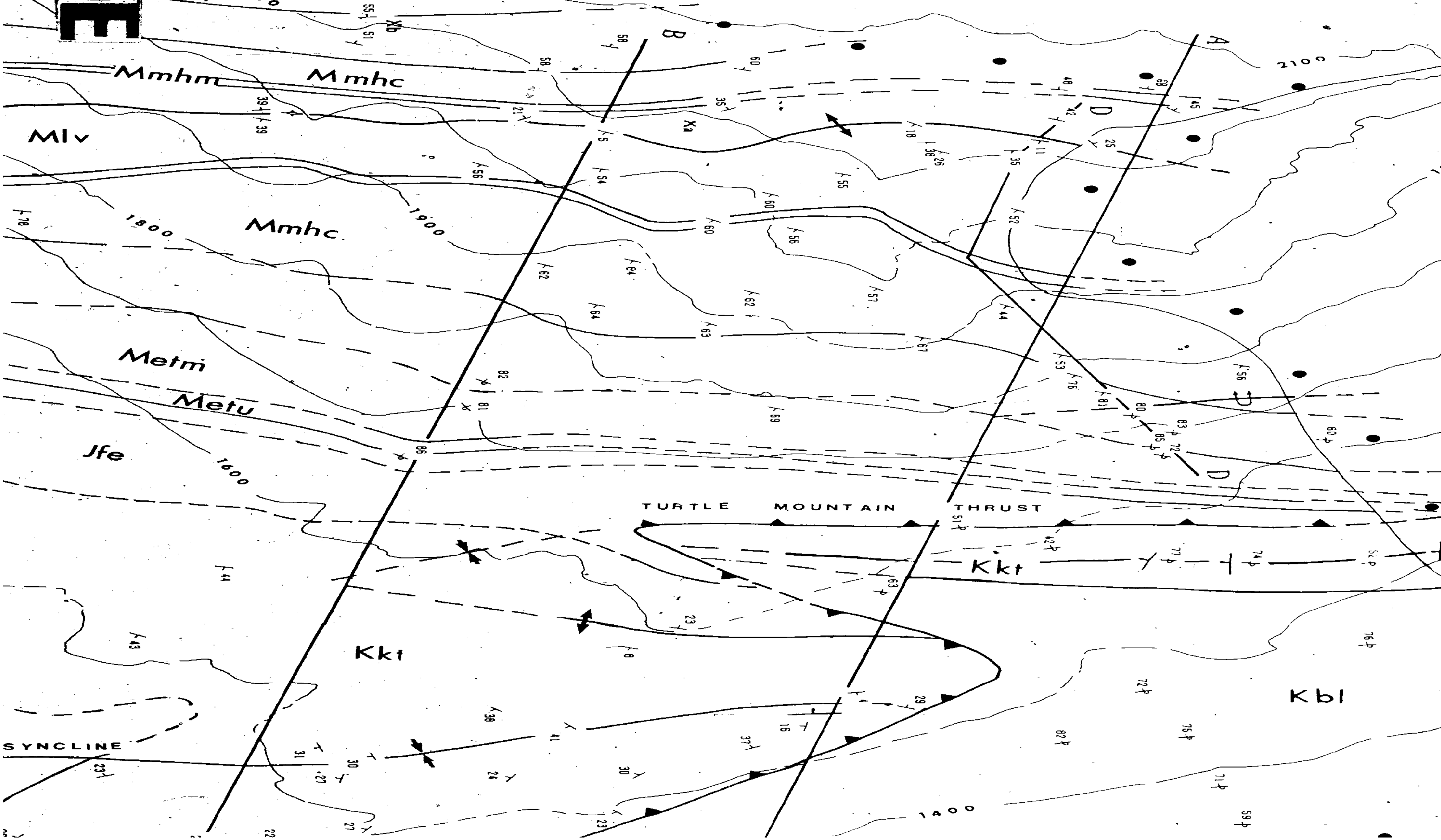
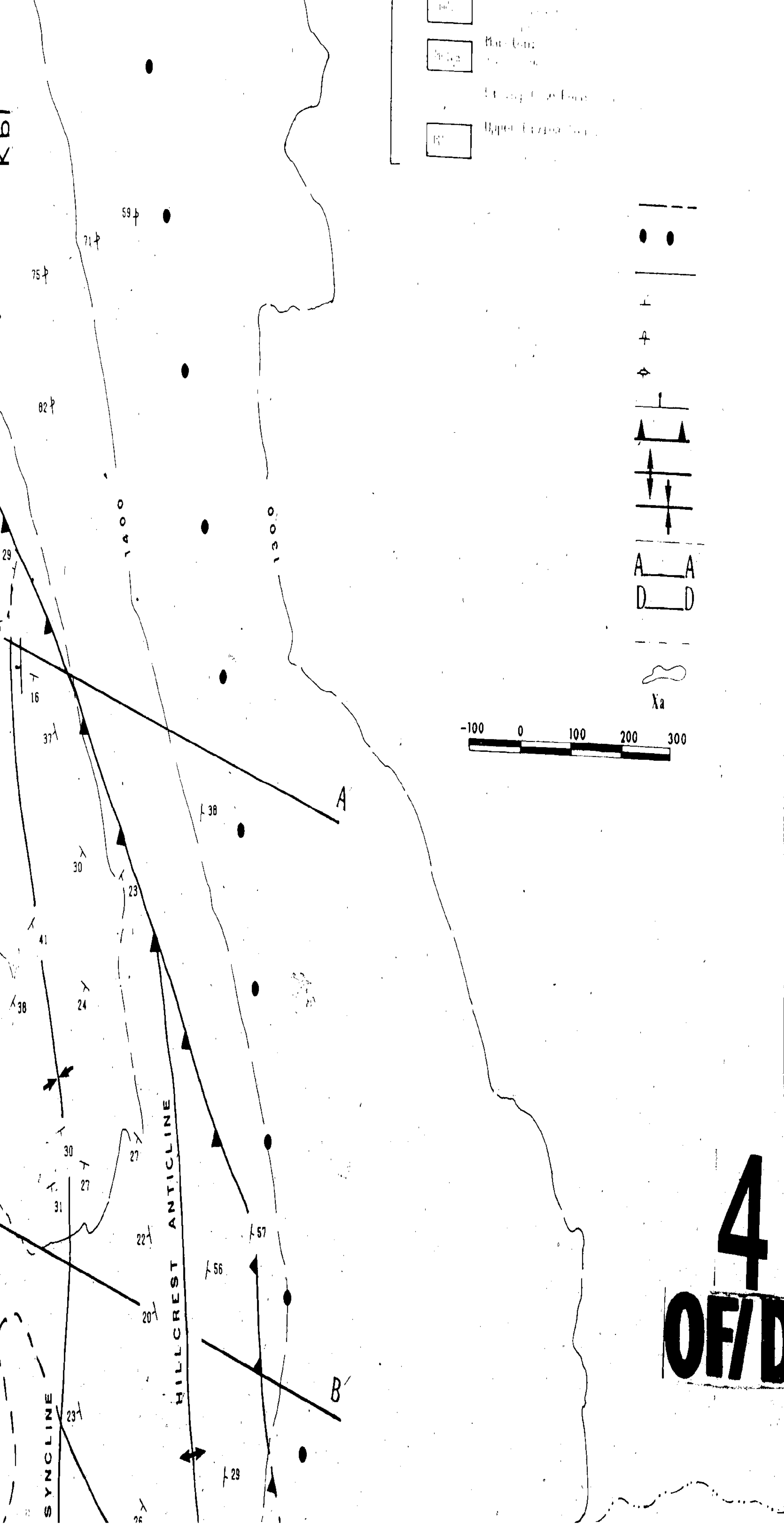

FRANK SLIDE
COAL
1400
1500
1600
1700
1800
1900
2000
2100
Kbl
A
D
D

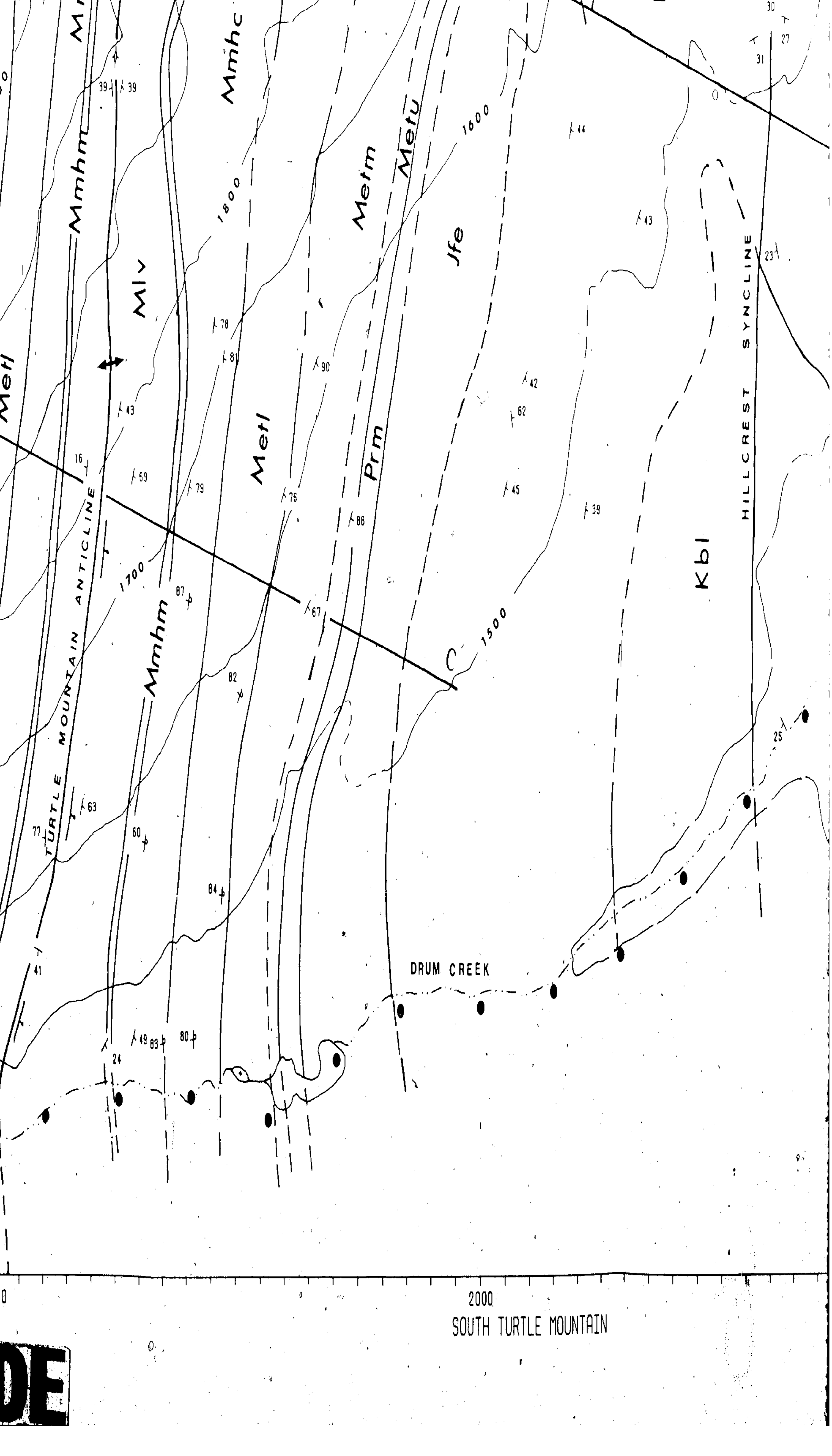
FIGURE 10


N
Upper Etherington:
Meta
Middle Etherington:
Metm
Lower Etherington:
Mount Head Formation
Carnarvon:
Marston:
Livingstone Formation
Upper Livingstone:
Mlv
59
71
75
82

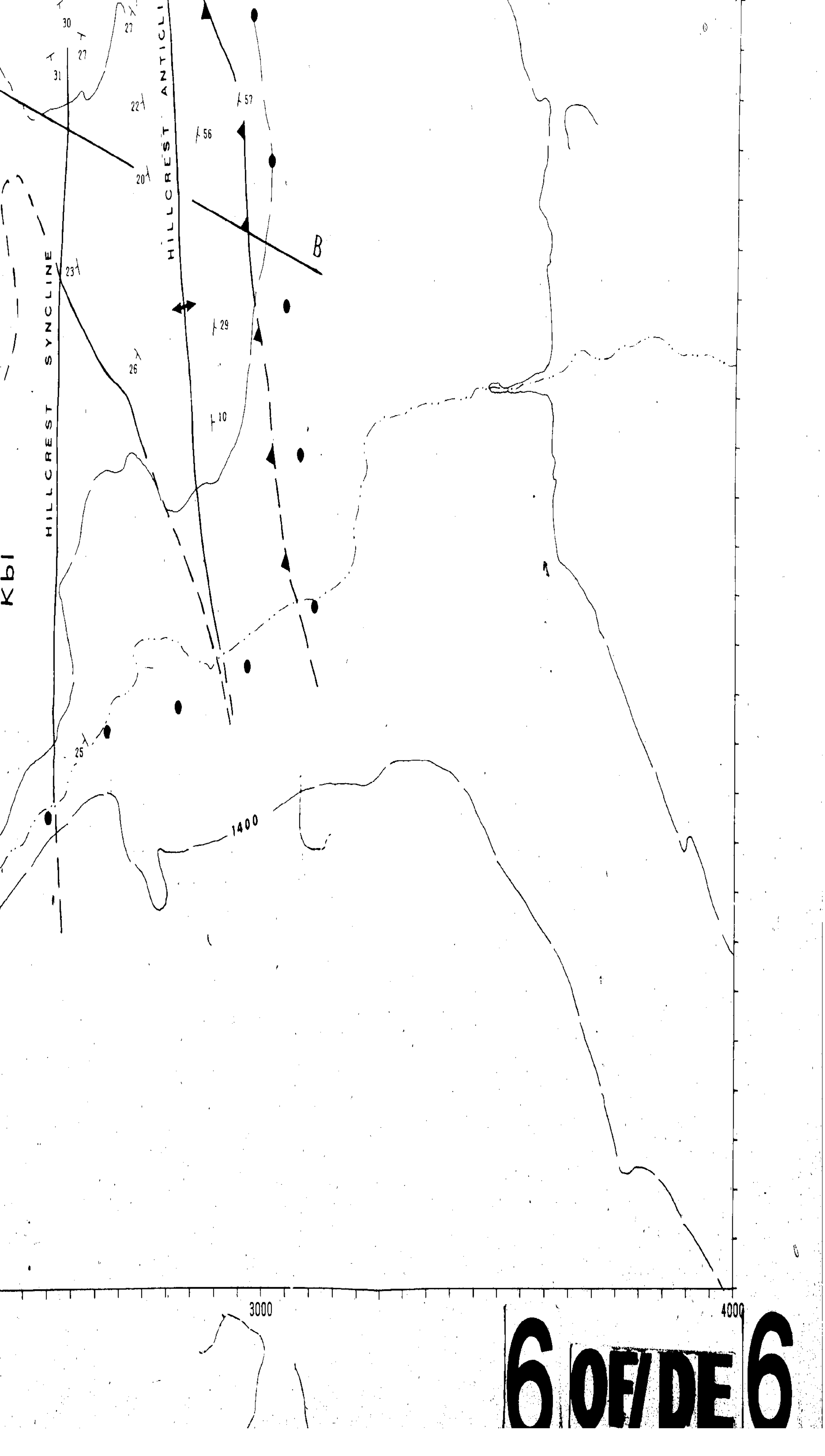

Mmhm
Mmhc
Mlv
Xa
Xb
Mmhc
Metm
Metu
Jfe
A
B
D
D
TURTLE MOUNTAIN THRUST
Kkt
Kkt
Kbl
SYNCLINE


Kbl
1400
1300
A
B
HILLCREST ANTICLINE
SYNCLINE
A——A
D——D
Xa
-100 0 100 200 300

4
OF/DE



Mmhc
Mmhm
Mlv
Metl
Metm
Metu
Jfe
Prm
Kbl
1800
1700
1600
1500
TURTLE MOUNTAIN ANTICLINE
HILLCREST SYNCLINE
DRUM CREEK
2000
SOUTH TURTLE MOUNTAIN


HILLCREST SYNCLINE
HILLCREST ANTICLI
B
Kbl
1400
3000
4000
6 OF/DE 6

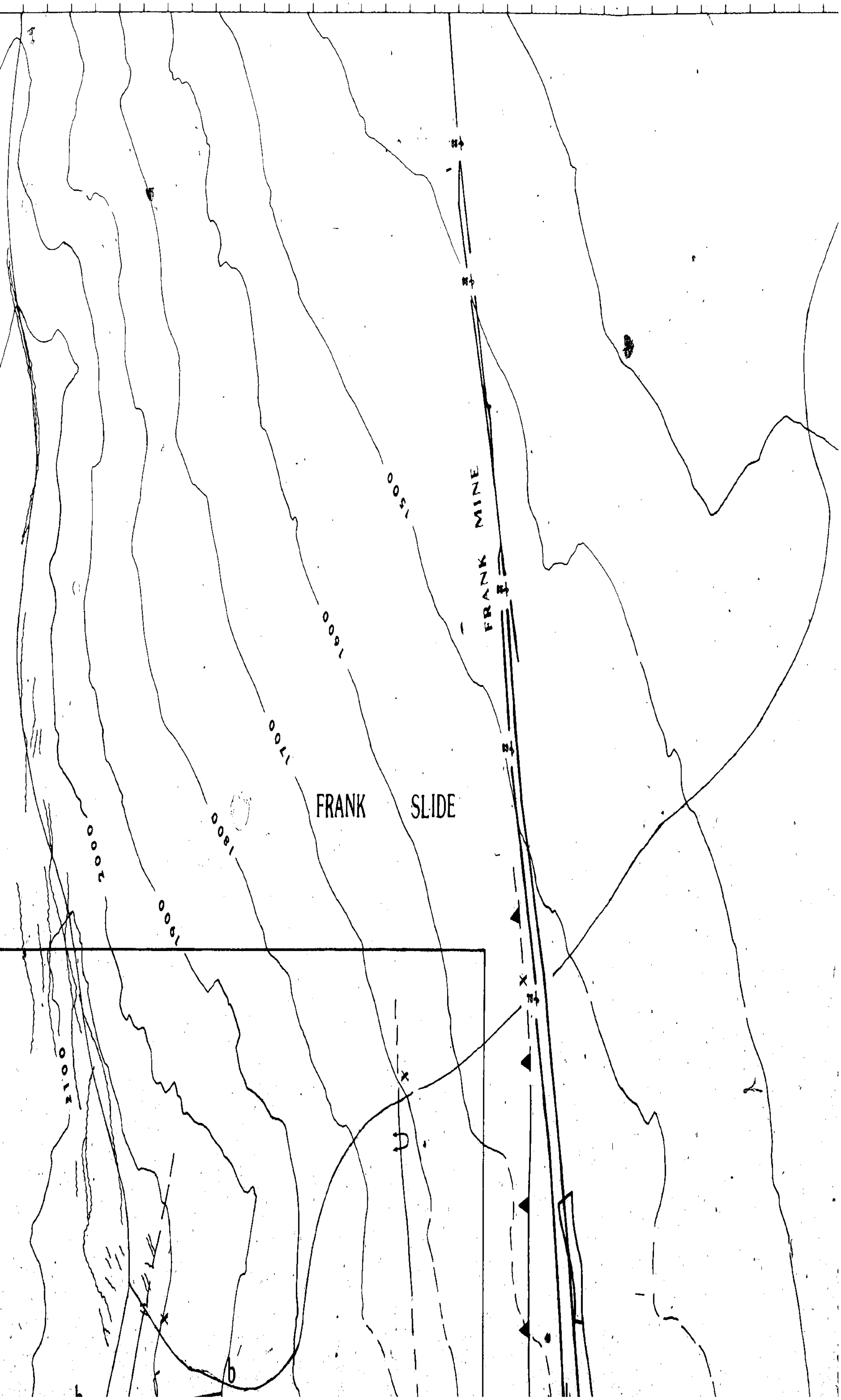
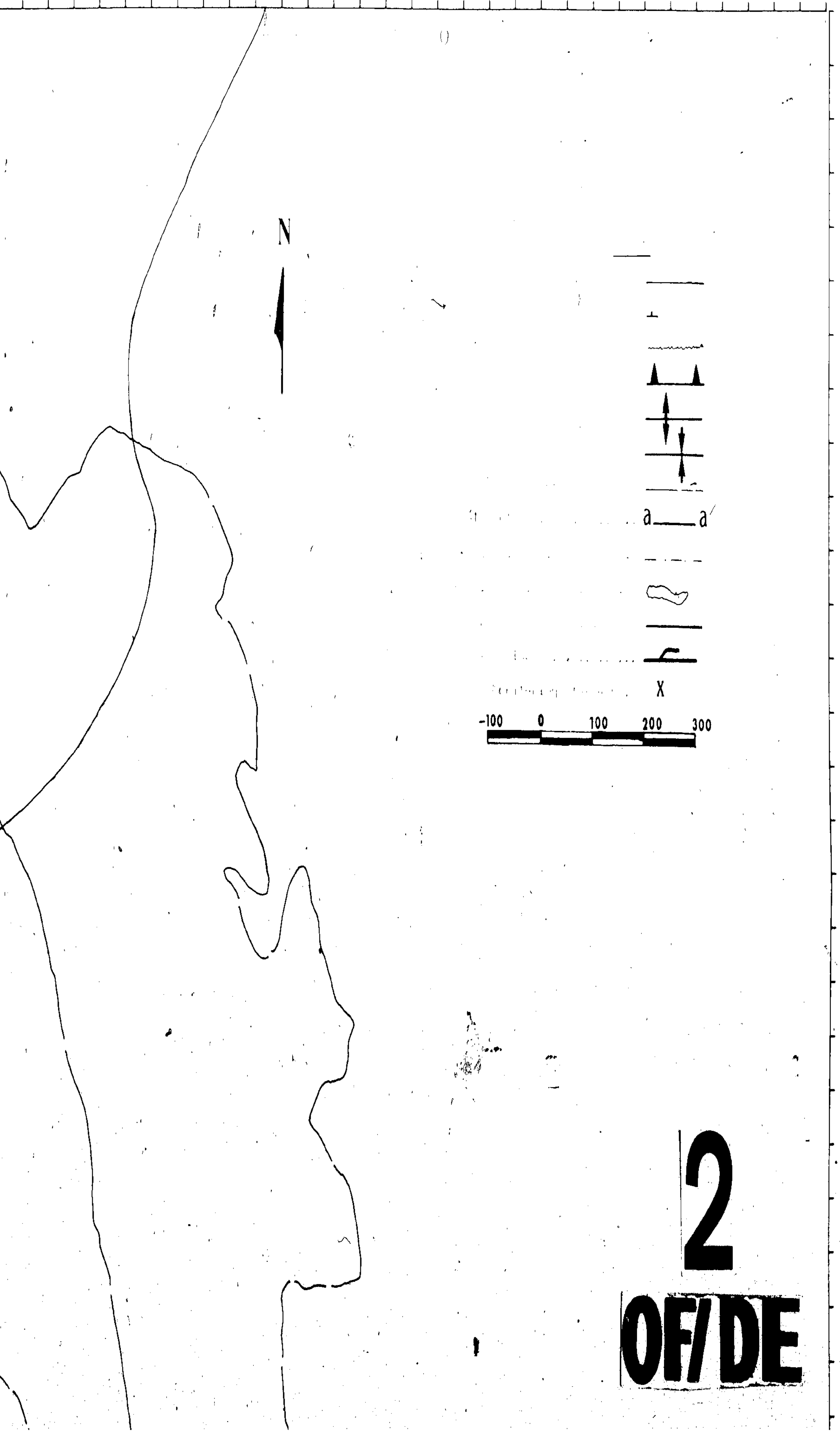
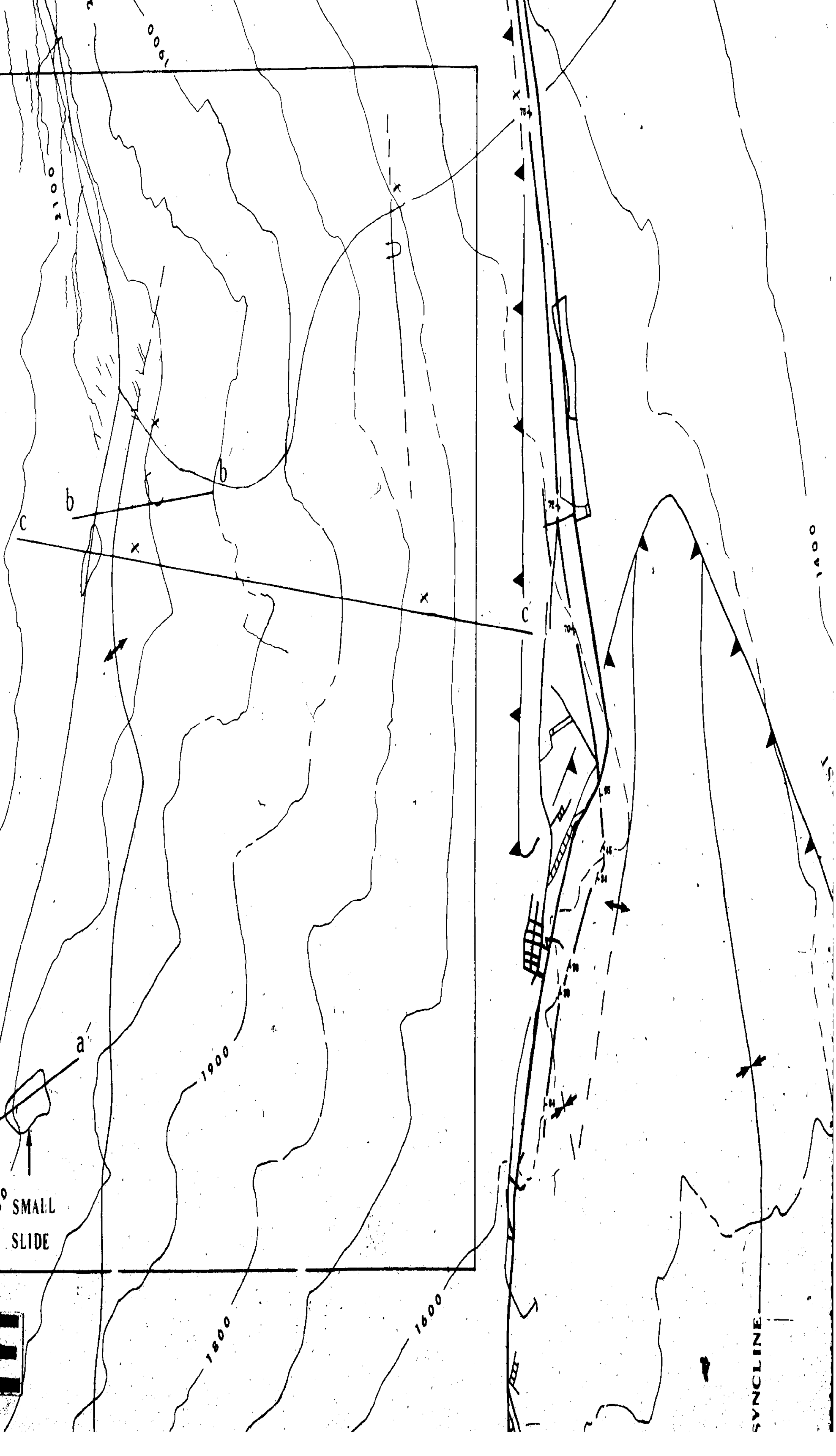

FRANK MINE
FRANK SLIDE
1500
1600
1700
1800
1900
2000
2100

FIGURE 11

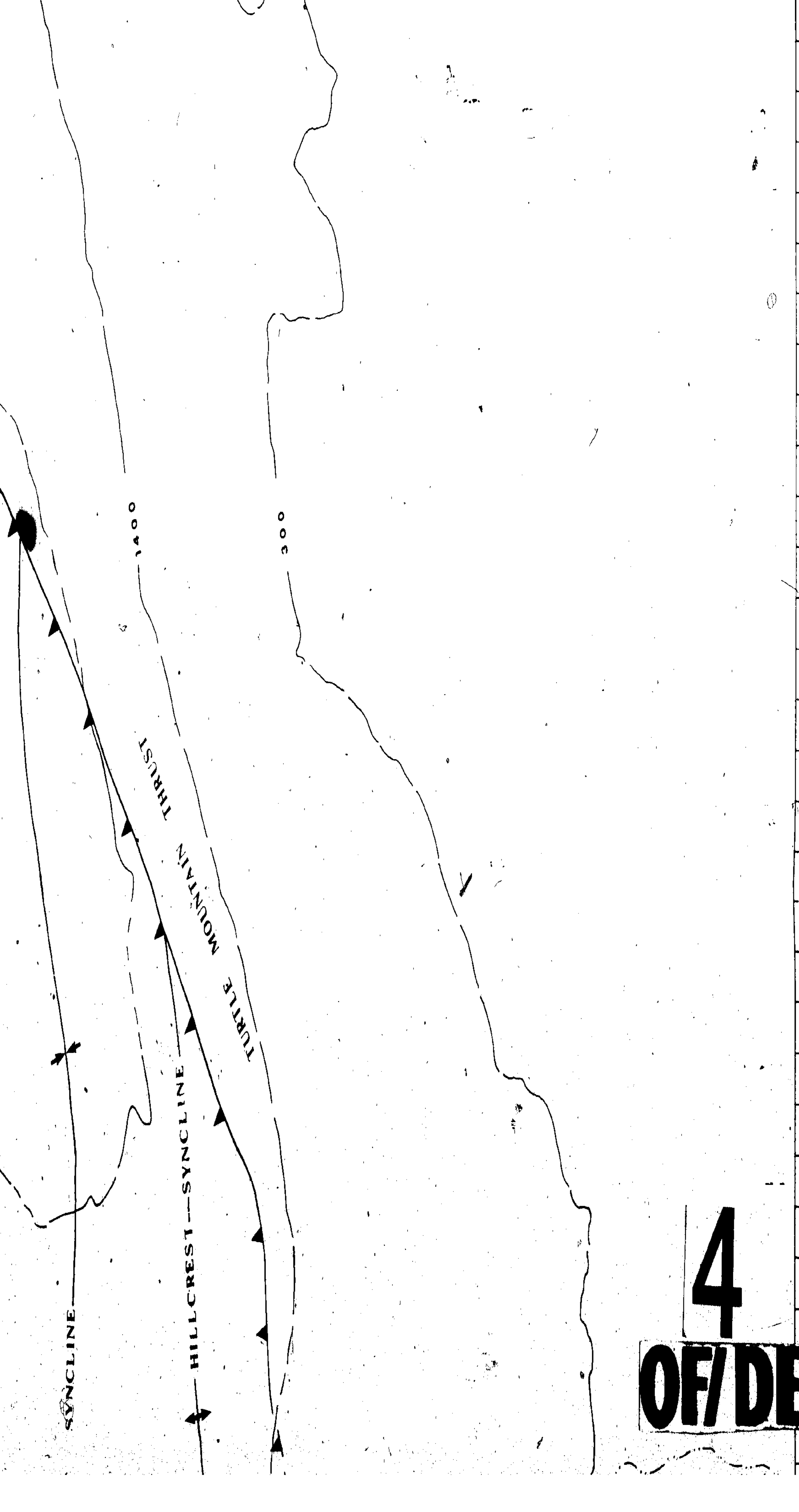


2

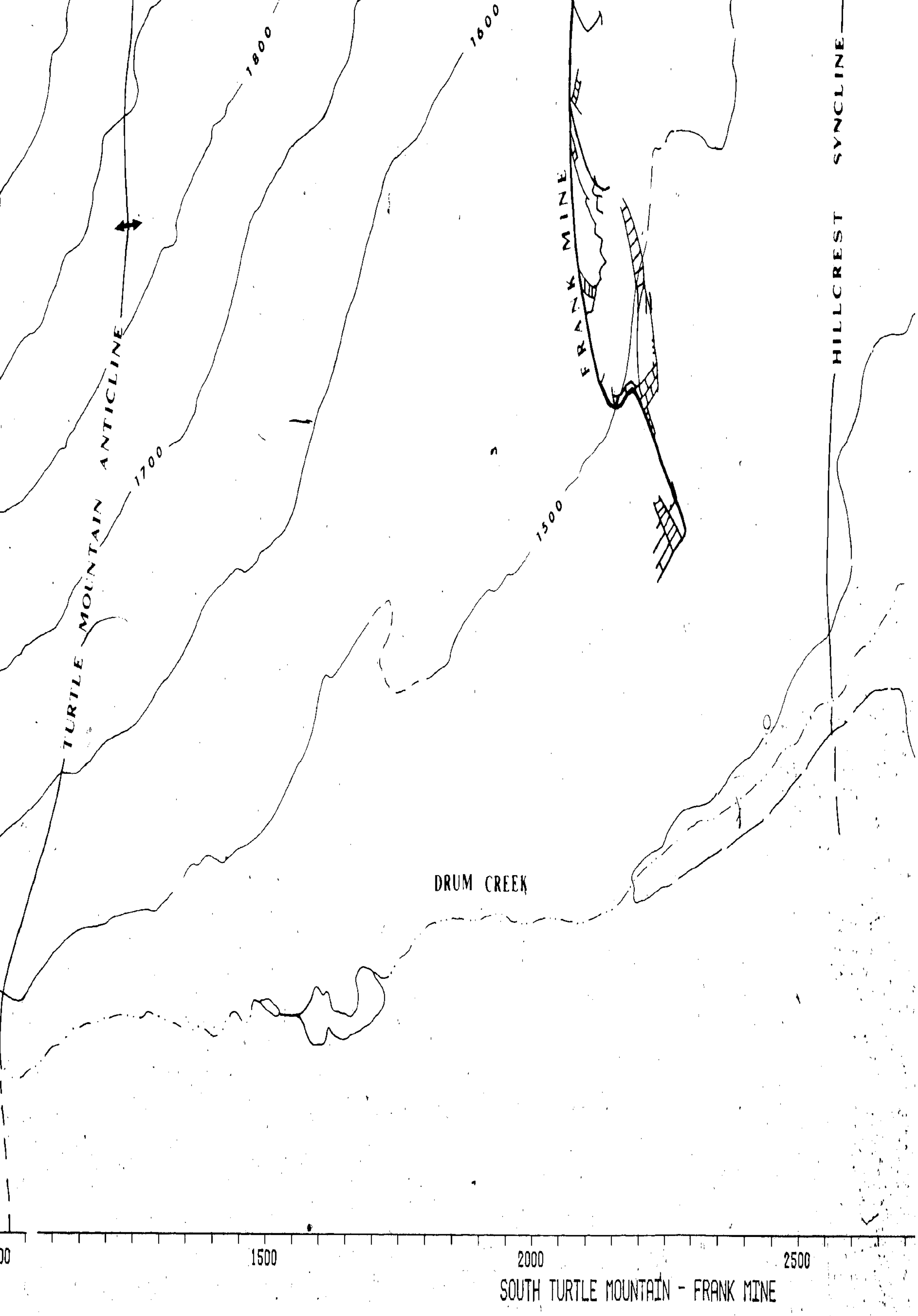
OF/DE



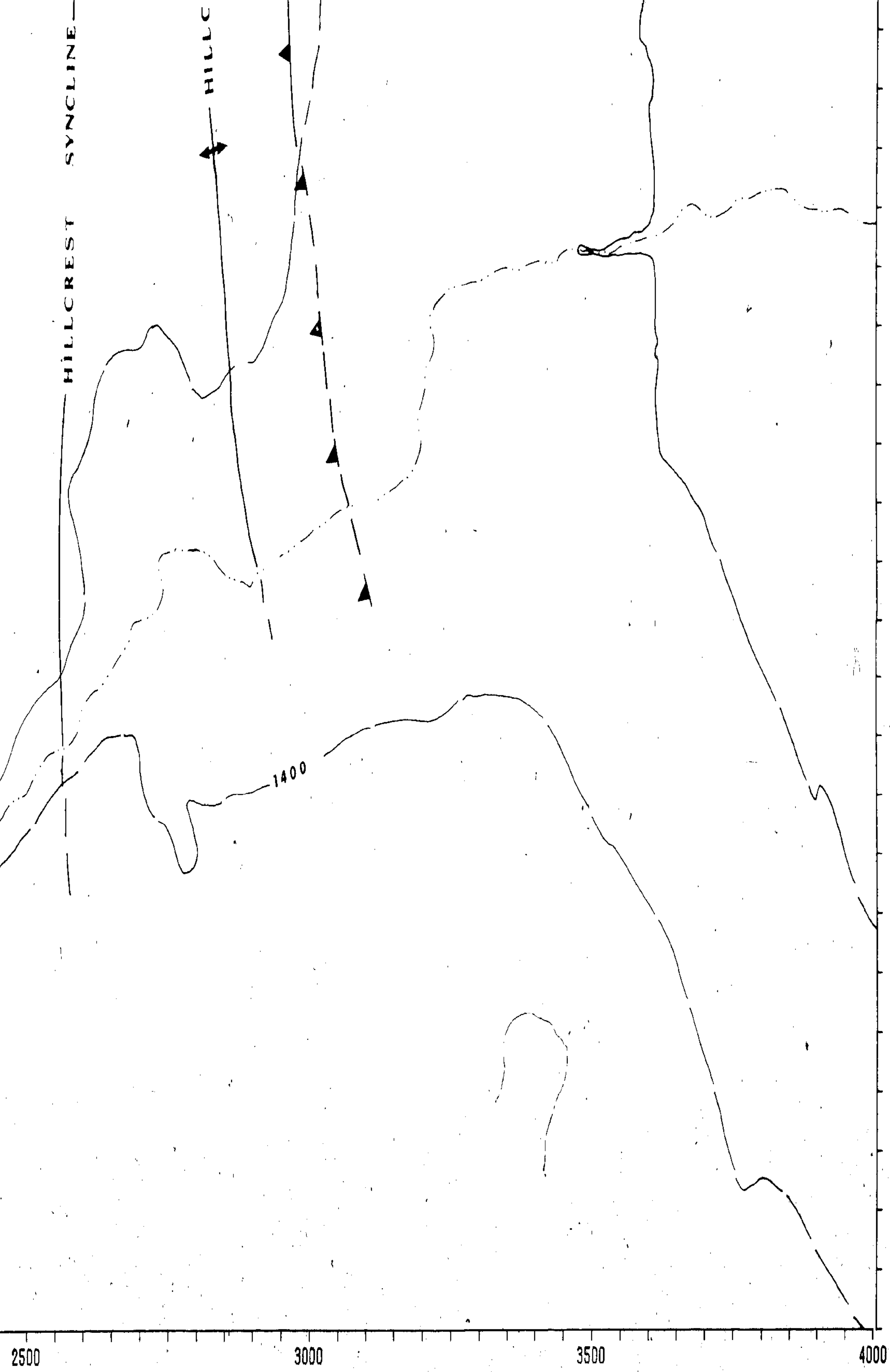
1900
2100
b
b
c
c'
a
SMALL
SLIDE
1900
1800
1600
1400
SYNCLINE


1400
300
TURTLE MOUNTAIN THRUST
HILLCREST SYNCLINE
SYNCLINE

4
OF/DE



1800
1600
1700
1500
TURTLE MOUNTAIN ANTICLINE
FRANK MINE
HILLCREST SYNCLINE
DRUM CREEK
1500
2000
2500
SOUTH TURTLE MOUNTAIN - FRANK MINE



6 OF/DE 6