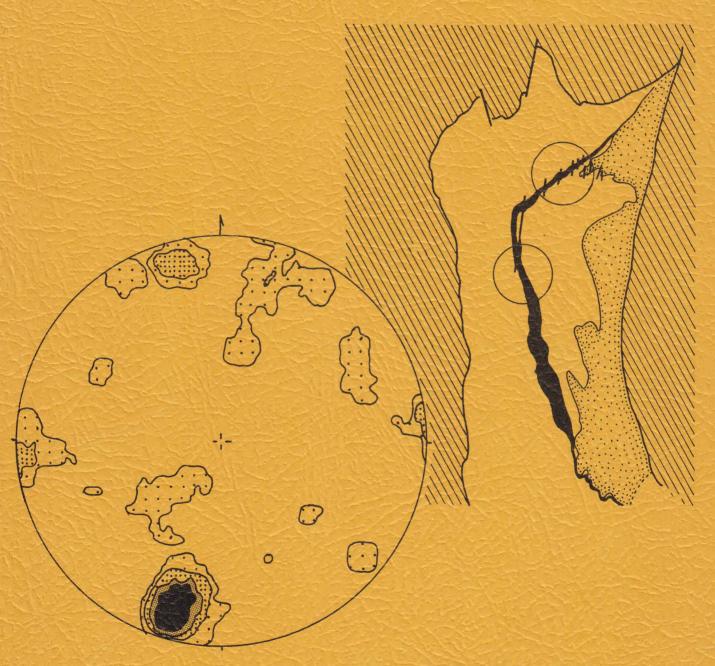
BRITTLE FRACTURE HISTORY OF THE MONTAGUE BASIN, NORTH-CENTRAL MASSACHUSETTS

BY ARTHUR G. GOLDSTEIN



CONTRIBUTION NO. 25
GEOLOGY DEPARTMENT
UNIVERSITY OF MASSACHUSETTS
AMHERST, MASSACHUSETTS.

BRITTLE FRACTURE HISTORY OF THE MONTAGUE BASIN, NORTH-CENTRAL MASSACHUSETTS

bу

Arthur G. Goldstein

Contribution No. 25

Department of Geology and Geography

University of Massachusetts

Amherst, Massachusetts

July, 1975

TABLE OF CONTENTS

	Page
ABSTRACT	viii
INTRODUCTION	1
The Problem	1
Location	1
Topography and Drainage	3
Regional Geology	3
Stratigraphy and Structure	6
Acknowledgements	11
METHODS	13
Field Forms	13
Joint Sampling Methods	18
Fault Sampling Methods	19
JOINTING	21
Method of Study	21
Regional Patterns	21
Patterns within Subareas	25
Eastern basement area	25
Turners Falls area	29
Cheapside area	29
Mt. Toby/Mt. Sugarloaf area	30
Western basement area	30
Relationship of Jointing in Sedimentary Rocks to Jointing in Crystalline Rocks	30

TABLE OF CONTENTS (Continued)

	Page
Separations of Classes of Joints	25
Turners Falls area	33
Cheapside area	33
Mt. Toby/Mt. Sugarloaf area	33
Western basement area	33
Eastern basement area	33
Correlations with Other Workers	34
Conclusions of Joint Study	34
Speculations on Significance of Joint Patterns	35
FAULT ANALYSIS	37
Introduction	37
Fault Occurrence	37
Fault Pattern within the Basin	37
Fault Patterns in Subareas	48
Geographic distribution of mapped faults	49
The Cheapside area	50
The Turners Falls area	50
Orientations of fault sets	54
Summary of Fault Patterns	54
Fault Related Structures: Folds	55
Significance of Fault Pattern: Mechanisms and Timings	63
Boundary conditions	63

TABLE OF CONTENTS (Continued)

	Page
Implication of the fault pattern	64
Tilting of fault sets	65
The horizontal compression	66
Orientations of stress during faulting	66
Complex tiltings	68
Curving stress trajectories	72
Speculation	73
SUMMARY, CONCLUSIONS AND OBSERVATIONS	77
Summary	77
Postulated Geological History	79
Suggestions for Future Study	81
REFERENCES CITED	82
APPENDIX I	85
APPENDIX II	99

ILLUSTRATIONS

Figure		Page
1	Map of Massachusetts showing location of Greenfield quadrangle and location of study area	2
2	Map of Connecticut Valley Basin showing volcanic rocks and Montague and Hartford Basins	5
3	Stratigraphic correlations between Montague Basin and Hartford Basin	9
4	Geologic map of Montague Basin	10
5	General Data Field Form	14
6	Planar Data Field Form	15
7	Linear Data Field Form	16
8	Block diagram illustrating relationship of conjugate faults and rotation axes	19
9	Map of strikes of joint sets in the Montague Basin	23
10	Composite plots of joint data	24
11	Joint data in subareas	26
12	Joint data from Onasch (1973) and Laird (1974)	28
13	Jointing above and below the Mesozoic unconformity	31
14	Composite plots of all faults, rotation axes, and slickensides	39
15	Plots of all clockwise rotation axes, their corresponding fault planes, and breakdown of these data into sets	41
16	Plots of all counterclockwise rotation axes, their corresponding fault planes, and breakdown of these data into sets	43

ILLUSTRATIONS (Continued)

Figure		Page
17	Diagrammatic sketch of thrust faults on cliff near Mountain Park, Greenfield	46
18	Summary of fault set orientations and motions	47
19	Fault data at Cheapside and Turners Falls	51
20	Diagram of fault set orientations at Cheapside and Turners Falls	52
21	Histograms of rakes of slickensides at Cheapside and Turners Falls	53
22	Block diagram and photograph of drape fold	56
23	Geologic map of Turners Falls showing location of major fold zones	58
24	Air photograph of fold zone #1	59
25	Air photograph of fold zone #2	60
26	Air photograph of fold zone #3	61
27	Photograph of hand sample and thin section showing cleavage	62
28	Orientations of fault sets and causal stresses at Turners Falls and Cheapside after rotation about the strike of bedding	67
29	Possible scenarios of multiple rotations of fault data	71
30	Map of Montague Basin showing orientations of principal stresses after rotation about the strike of bedding	74
31	Dip-slip motion imposed on pre-existing fractures by external rotation	76

TABLES

Number		Page
1	Characteristics of subareas	27
2	Orientations of fault sets at two subareas	54

ABSTRACT

Orientations and motions of 313 minor faults have been recorded in the Mesozoic Montague Basin of northwest Massachusetts. Two areas at Turners Falls (TF) and Cheapside (C) were sampled intensively. Each area has two sets of minor faults, interpreted as having a conjugate relationship. A right-lateral set has a mean strike of N2OW (TF) and N3OW (C), whereas a left-lateral set strikes N5OE (TF) and N3OE (C). In the TF area the NE set also shows right-lateral displacement, possibly as a younger motion. The mean σ_2 orientations for all these strike-slip fault sets are normal to the 30°- to 40° -dip of bedding. This relationship suggests that either there was a chance regional deflection of the σ_2 stress trajectory at the time of faulting or, more likely, that the strike-slip faulting took place while bedding was still horizontal and σ_2 was vertical. Numerous normal faults appear prominently only in the TF area and are parallel to the NE-trending strike-slip faults. These down-to-the-west faults with associated drape folds are interpreted as mechanisms associated with complex tiltings of the TF area with respect to the rest of the basin.

About 3000 joints were sampled throughout the basin. At many outcrops major sets strike N70-85W and N65E. Only in the area surrounding TF is a N30E set common. The joints of that area are normal to bedding, suggesting an origin prior to major tilting. In the remainder of the basin some joint sets are normal to bedding whereas others are vertical, suggesting that jointing spanned the era of regional tilting.

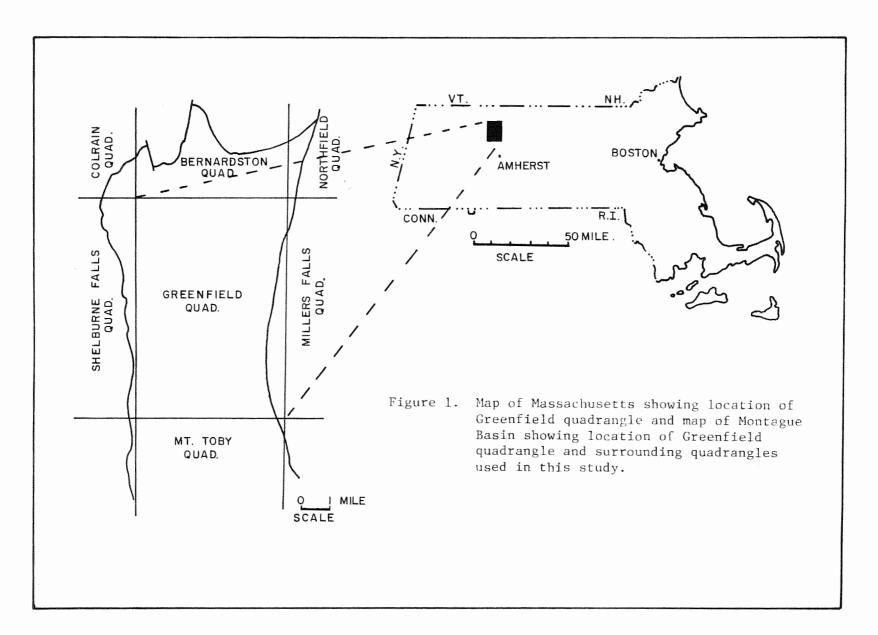
INTRODUCTION

The Problem

Many people have had numerous and varied interpretations of the faults and their associated motions within and surrounding the Montague Basin. A primary goal of this study is to determine the kinematics and history of faulting by recording data on numerous small faults within the Mesozoic rocks. These data should have implications for large faults, their motions, timing, and their relationship to the basin tectonics. An additional goal of this study was to interpret joint patterns in the sedimentary rocks in an attempt to correlate these patterns with the faulting and with previous joint observations to the east (Laird, 1974; Onasch, 1973; Ashenden, per. comm., 1975), to the west (Pferd, per comm., 1975) and to the south (Piepul, 1975; Naso, per. comm., 1975).

Location

The study area (Figure 1) lies in north-central Massachusetts, primarily in the Mt. Toby, Greenfield, and Bernardston 7 1/2-minute U.S.G.S. quadrangles, with minor portions in the Millers Falls, Northfield, Colrain, Shelburne Falls, and Williamsburg quadrangles. The area extends from Bull Hill Road in the town of Sunderland, Massachusetts, in the south to the town of Bernardston, Massachusetts, in the north and from the foothills of the Berkshires on the west to the Pelham Hills on the east.



Topography and Drainage

The area forms a topographic lowland surrounded by the low hills of Mount Warner on the south and highlands on the east, west, and north.

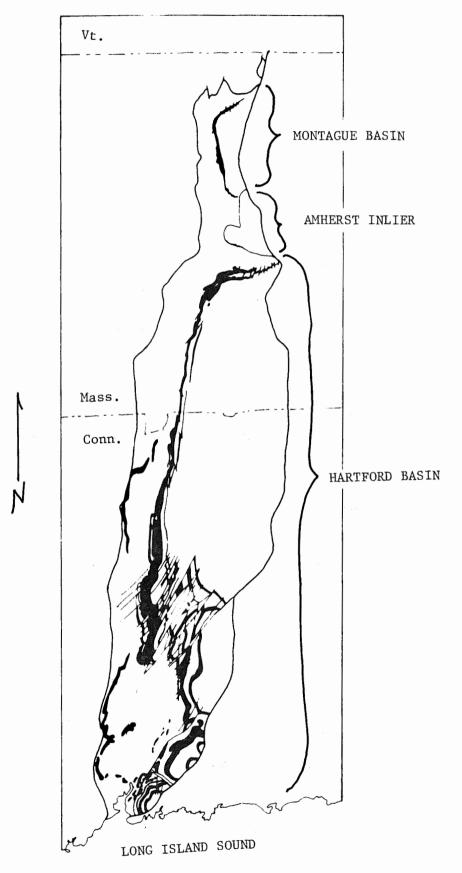
Within the valley itself, a prominent ridge, the Pocumtuck Range, is oriented nearly north-south, but in the north-central portion of the basin the orientation of the ridge changes abruptly to approximately N60E. The southern extremity of this ridge is Mount Sugarloaf. In the southeast corner of the area, Mount Toby forms another prominent highland with a relief of approximately 300 meters.

The Connecticut River flows through the entire area and is fed by several smaller rivers such as the Millers River, the Falls River, and the Deerfield River.

Regional Geology

A number of unmetamorphosed sedimentary basins are present in the metamorphic terrains of the southern, central, and northern Appalachians and are elongate parallel to the structural grain. The basin rocks are commonly cut by faults and have been locally warped into large amplitude folds and tilted by as much as 60°. The basins, sometimes referred to as "half-graben," are all fault-bounded on at least one side (Sanders, 1963) and are tilted toward their border faults. Basic volcanic rocks are common as lava flows and sills. These basins formed during the late Triassic-early Jurassic and are believed to have formed in response to the rifting of North America from Africa and Europe (May, 1971).

Figure 2: Map showing outline of Connecticut Valley Mesozoic Basin and the distinction between the Hartford and Montague Basins. Basic volcanic and intrusive rocks are shown in black.



The Connecticut Valley Mesozoic Basin extends from near the Vermont border to Long Island Sound. The study area is a separate part of the Connecticut Valley Basin, called the Montague Basin (Emerson, 1898) (Figure 2). It is approximately 14 kilometers wide and 24 kilometers long, whereas to the south the Hartford Basin is 32 kilometers wide and 113 kilometers long. Stratigraphy differs between the two basins. The Hartford Basin has several volcanic units, including welded tuff, whereas the Montague Basin has but one volcanic unit (Figure 3). Stratigraphic correlation between the two basins is uncertain as they are separated by a block of metamorphic basement called the Amherst Inlier.

Stratigraphy and Structure

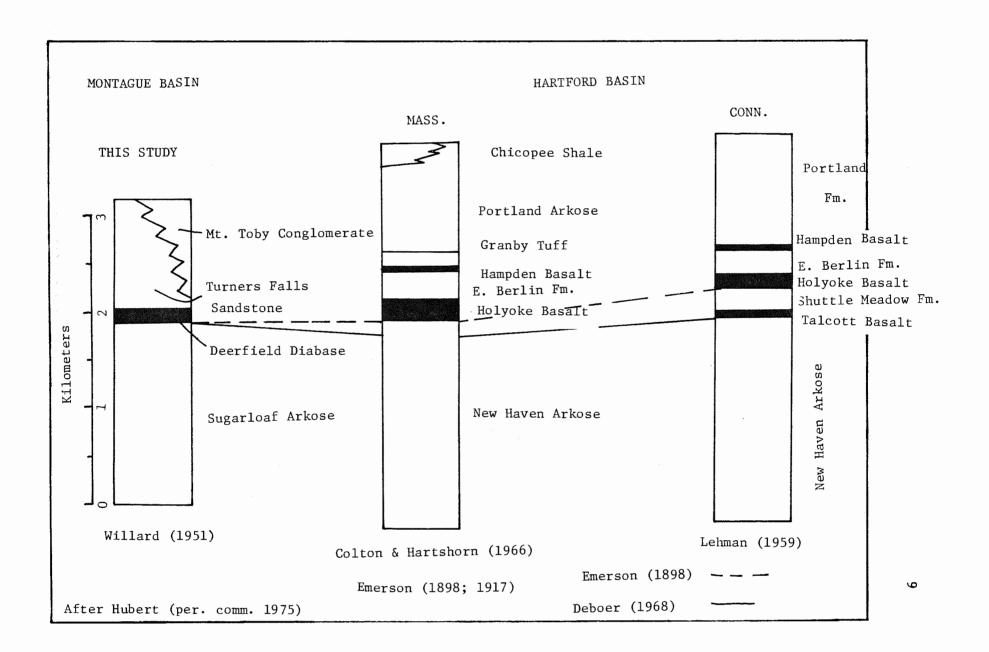
Emerson (1898) first mapped the region, including the study area. He defined the main stratigraphic units, a thick lower unit of coarse conglomerate, a volcanic flow, a thick unit of well-bedded ferruginous sandstone, and an upper unit of massive coarse conglomerate. These are known respectively as the Sugarloaf Arkose, the Deerfield Diabase, the Turners Falls Sandstone, and the Mount Toby Conglomerate.

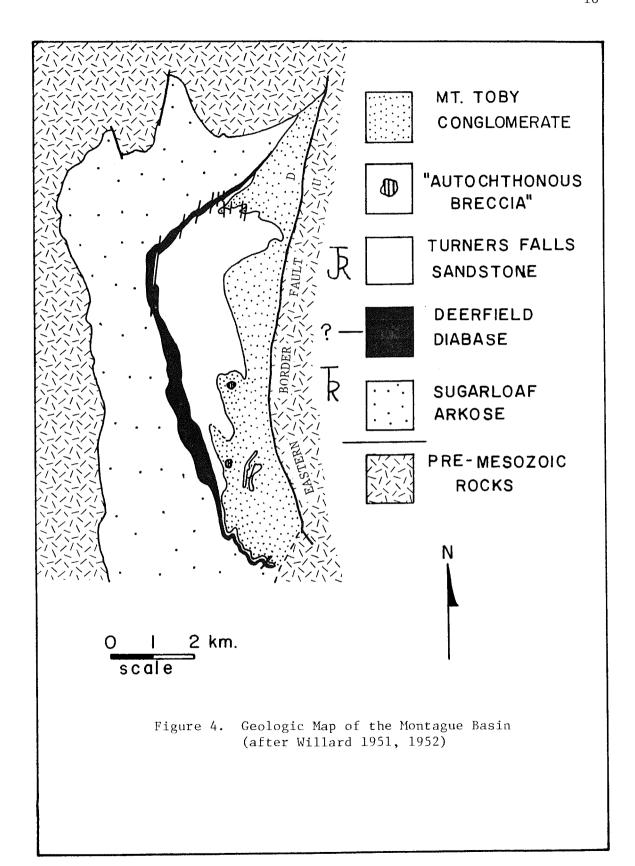
Willard (1951, 1952) mapped the Mt. Toby and Greenfield 7 1/2-minute quadrangles, which cover most of the Montague Basin. His stratigraphy and possible correlations are shown in Figure 3. The structure of the basin is basically that of an east-dipping arcuate basin, bounded on the west and partially on the north by angular unconformities. On the east and in some northern areas it is fault-bounded. The eastern border fault has received much attention and has been referred to as

a normal fault (Emerson, 1898; Willard, 1951, 1952; Robinson, 1967; Laird, 1974; Keeler and Brainard, 1940; Wheeler, 1939; Wessel, 1969; Sanders, 1960, 1963), a right-lateral strike-slip fault with a minor dip-slip component (Bain, 1957), a normal fault with a right-lateral component (Ahmad, 1975), a high-angle reverse fault (Bain, 1932), an unconformity (Northeast Utilities, 1974) and a west-dipping thrust fault of Paleozoic age (Northeast Utilities, 1975). This fault is a poorly understood and complex feature, the precise nature of which is beyond the scope of this study.

Faults are numerous within the basin and can be mapped clearly by offsets in the Deerfield Diabase (Figure 4) (Willard, 1952). Among the largest are the Falls River Fault and the Temple Woods Fault (Figure 4). Willard (1952) calls these normal faults and calculated 800 feet (243.8 m) of vertical displacement on the Falls River Fault from horizontal offset of the contacts. He found no evidence that these faults predate deposition of at least the volcanic unit and overlying sandstone. However, he does infer that the Falls River Fault extends to Whitmore's Pond in the southern part of the basin and possibly farther. He believes the fault is related to a major "basin-forming fault" which occurred before sedimentation and experienced additional motions which deformed the overlying cover rocks. This interpretation was based heavily on the presence of "autochthonous breccia" (Reynolds and Leavitt, 1927) east of this inferred fault on Taylor Hill in Montague and near Whitmore's Pond, indicating shallow pre-Triassic basement. West of the inferred fault, a well in Greenfield, Massachusetts, penetrated 875 feet (266.7 m) to stop

Figure 3: Stratigraphic columns of the Montague Basin and the northern and southern Hartford Basin showing suggested correlations.





in Triassic rocks (Emerson, 1898). Bain (per. comm., 1974) also postulates a major buried fault at this location. Recently, a well was drilled through an outcrop of "autochthonous breccia" on Taylor Hill approximately one kilometer east of Montague Center, Massachusetts. It penetrated 45 meters of the monolithologic breccia and passed into Triassic conglomerate and sandstone beneath (Northeast Utilities, 1975). Clearly, basement is not as close to the surface in these areas as the previous authors thought; hence, the presence of a major buried fault seems less likely. Robinson (per. comm., 1974) believes the monolithologic breccias to be a land-slide deposit.

Two faults in the Mount Toby area shown by Willard (1952) have been interpreted by Wessel (1969), however, as conformable contacts. The exact nature of these faults or contacts is ambiguous. Wessel (1969) also inferred the presence of a major fault scarp on the eastern border of the basin during deposition of the Mt. Toby Conglomerate, based on sedimentary criteria. Thus, his conclusion was that at least some faulting along the eastern basin border was syndepositional, a conclusion similar to that of Emerson (1898).

Acknowledgements

I wish to thank Dr. Donald U. Wise, who has helped me greatly throughout every aspect of this project, given me the freedom to form my own opinions, but has been there when I needed help. I owe a special debt of gratitude to Jeffrey Pfred and Robert Piepul, who have introduced me to computer geology and spent many hours helping me with

computer-related problems. Without the field forms devised by
Pferd and the programs written by Piepul, this study would have
been tedious and time consuming. Field assistance was provided by
Brian Wood. Dr. G. E. McGill has acted as a second advisor, helped
with money matters, taken air photographs, and critically reviewed
the thesis. Dr. J. F. Hubert and Dr. J. Hartshorn have also critically reviewed the thesis. Financial support was provided by a grant
to Hampshire Geological Associates from the Northeast Utilities
Service Company. I also thank E. D'Appolonia Consulting Engineers,
Inc., my present employer, for providing typing and drafting expertise
for the preparation of the final manuscript.

METHODS

Field Forms

A preexisting computer-based data storage and retrieval system (Pferd, 1975) was modified by Piepul to accommodate brittle structural elements more readily. Orientations and characteristics of these structural elements were recorded in a coded manner on field forms (Figures 5, 6, 7). Every location (sampling site, station) was given a unique number which, along with characteristics of the outcrop, notes, and sketches, was recorded on the general data form (Figure 5). Various types of data were recorded for each fracture element on the planar data form (Figure 6); the "A" code is the type of fracture, i.e., fault, joint; the "B" code is the rock type in which the fracture formed; the "C" code is the surface character code, e.g., rough, smooth, brecciated, quartz mineralized, epidote mineralized; the "Q" codes are used to record quantitative data, Ql being the type of measurement (size, spacing, displacement, etc.) and Q2 being the actual quantity. The orientation is then recorded in the next five columns. Strike is noted as the azimuth of the plane when the dip was to the right. Thus, a joint striking N30E could be noted as 0300 when the dip was to the southeast or 210° when the dip was to the northwest. The last column in each line was for a "tag" which gives a unique name to particular measurements. Thus, notes recorded on a fracture at station 1 with tag Q would be called 10 or a fault tagged 10 could be related to a slickenside measurement tagged 10, recorded on a linear data sheet (Figure 8).

	CODES		
	Type of outcrop	GENERAL DATA	1111
Size 1 <1m.	1 natural - seacoast		parameter de la constitución de
2 1-5m.	2 natural - inland	Station Number	
3 5-10m.	3 roadcut	Commence of the Commence of th	5
4 10-20m.	4 quarry - abandoned		
5 2Ø-5Øm.	5 quarry - operating		
6 >5¢m.		Joint development Date	3
	Comments		
Auxiliary information	G general	Outcrop Size	Type 14
1 sketch	F folds	L_13	
2 photograph	L lineations	Auxiliary information	
3 sample	P planer elements		
4 separate sheet	Followed by box number	Comments:	
	where additional comment		
Joint development	is to be made.	CONTRACTOR OF SECURITION OF SECURITION OF SECURITION OF SECURITIES SECURITION OF SECURITION OF SECURITIES SECU	emments and a second s
I very massive	Eg.		
2 slighted jointed	6 2 5	анизмуниция/при вин+закорайция дартнятрогорова преволей раздину прогоставления	
3 moderately jointed	AND THE PERSON NAMED AND THE P		
4 well jointed	C O M		ambientere eminimismo eminimismo 42
5 very well jointed	Manufacture de la constitución d		
	M E N	generationals distilluisionisti to reproductive qui qui que que que constituente que que que que que que que q	analusaminus aminomentum quantum 51
Notes:	And the state of t		
Notes, sketches, or	T	 Ответительный при при при при при при при при при при	entrational designation of the contration of the
important information	COMPACT COMPANY DESCRIPTION OF A COMPANY OF THE PROPERTY OF TH		4.
that does not fit into the form or comments		Ministrativo de la company	
section. Use reverse side of general sheet		71	
if more space is require	ed .	Neter	
II more phone in reduction	at von B	Notes:	

Figure 5. General Data Form

page	number	
		73

PLANAR DATA CODES			ΡI	ΑN	ΙΔ	R	DATA	`	3
A=SURFACE FEATURE ### B bedding/foliation 5 dike/voin 7 axtal plane 2 fault 8 slip cleawage 4 colomar joint 5 tabular inclusion 5 microjoint 8 microjoint 6 microjoint 7 microjoint	GARACTER CODES Galcite 5 zeolite 1 chlorite 7 quartz/chlorite 2 epidot 8 zeolite/chlorite 3 Fe-stain 9 other 4 pyrite A smooth 5 quartz 8 rough		Statio			Q1 Q 2	STRIKE	DIP	TAG
B-ROCK TYPE use rock type codes C=DESCRIPTORS when A=0: B-1 massive 2 faintly bedded/foliated 3 moderately bedded/foliated 4 well bedded/foliated 5 extremely well bedded/foliated A=1-4, B use character codes A=5-6 use rock type codes A=7-8 B=blank A=9 B=1 slope of topography 3 2 cliff face A=A B=1 cift 2 grain 3 hards	5 5cm. I lm. 6 6cm. J 2m. 7 7cm. K 4m. 8 8cm. L 6m. 9 9cm. M 8m. 4 10cm. N 10m. 8 15cm. O 15m. c 20cm. p 20m.	7 30m. R 40m. S 50m. T 1cm. U 2cm. V 5cm. W 7.5mm. X gr. 50m. Y small undetermined large undetermined							16 27 38 49
Q1=TYPE OF MEASUREMENT FOR Q2 1 length of surface in outcrop 2 thickness/dilation distance 3 distance to next coplanar surface 4 distance to next coplanar surface 5 distance to next cocharacter surface 6 vertical displacement on fault 7 spacing within joint zone Q2= MEASUREMENT VALUE use quantitative codes STRIKE 360° azimuth taken with dip to right DIP angle of inclination	B gneiss O aplite (C amphibolite P quartz pl p achist Q quartz d: E quartzite R gneiss in F sandstone S amphibol: G shale T schist in H conglomerate U quartzit: I basalt V sandston J pink pegmatite W shale in	ike/vein nclusion ite inclusion nclusion e inclusion e inclusion clusion clusion rate inclusion dike							60
TAG letters from A-Z; number from 0-9; aster on next line. 1. footnote for comment on GEMERAL dat. 2. give lineations same TAG as associal 3. for up to 2 more lines of C codes at of Q1 and Q2 codes, place asterisk preceding each line of additional a) no * in last line of data. A TAG may be entered here	a sheet. ted plane. nd up to 6 more lines (*) in TAG column data.			•			page number		73

Figure 6. Planar Data Form

LINEAR DATA CODES A-LINEAR FEATURE 1 fold axis 2 rotation axis	LINEAR DATA	4],
3 slickenside 4 plumose structure 8-DESCRIPTORS When A=1 B=fold type: 1 drag on fault 0 UANTITATIVE CODES 0 0 0 30m. 0 30m. 0 40m.	Station Number 5	5
2 chevron/kink 2 2cm. F 50cm. S 50m. 3 isoclinal 3 3cm. G 65cm. I 1mm. 4 concentric 4 4cm. B 80cm. U 2mm. 5 broad warp 5 5cm. I 1m. V 5mm. 6 6cm. J 2m. W 7.5mm. A*2 B**certainty code for 1 excellent 7 7cm. K 4m. M gr. 50m. rotation scame: 2 good 8 8cm. I 6m. Y small	A B C Q1 Q2 TREND PLUNGE TAG	
3 poor 9 9cm. M 8m. undetermined A=3 B=fault movement 1 strike-slip A 10cm. N 10m. Z large direction: 2 oblique-slip B 15cm. O 15m. 3 dip-slip C 20cm. P 20m. A=4 B=blank		'16]
C-MOVEMENT SERSE/PROPAGATION DIRECTION when A=1-2 C-rotation sense: 1 clockwise 2 counterclockwise A=3 C-fault motion 1 sormal 5 up on B mense: 2 reverse 6 up on E]38
(for combi- 3 right-lateral 7 up on S nations see 4 left-lateral 8 up on W TAG) And Copropagation direction U stem up plunge of plummee structure: D stem down plunge		49
Q1-MEASUREMENT TYPE CODE FOR Q2 (see TAG) 1 wavelength of fold 2 amplitude of fold 3 net displacement on fault Q2-MEASUREMENT VALUE		60
use quantitative codes TREND arisant of lineation pointing down plungs PLUNGE angle of inclination		71
TAG letters from A-3; numbers from \$-9; autorisk (*) for data continued on next line. Usest 1 footnote for comment on GENERAL data sheet. 2 give lineations some TAG on associated plane 3 for up to two more lines of C, Q1, and Q2 codes, place asterisk (*) in TAG column preceeding each line of additional data. (a) no * in last line of data. A TAG number or letter may be entered here.	page number	73

Figure 7. Linear Data Form

Only two linear structural elements have been recorded for this study: slickensides of faults and rotation axes of faults (Wise, 1965). Although the rotation axis was first described for use in thin-section petrofabric analysis by Wise (1965) as a method of detecting conjugate glide planes in deformed calcite crystals, it is also applicable to brittle structural analysis. The rotation axis of a fault is an imaginary lineation perpendicular to the slickensides and lying in the plane of the fault. If no multiple motions have occurred along the fault, this orientation is that of σ_2 at the time of faulting. When the relative sense of displacement along a fault can be determined by stratigraphic offset, drag, drape structures, or the character of the slickensides, the rotation axis will have a determinable rotation sense when viewed down plunge. Figure 9 shows a pair of strike-slip faults with the same orientation of rotation axes but opposite rotation senses. If two faults are conjugate, they have formed under the same stress field and their σ_2 orientations (rotation axis orientation) will be coincident. Further, their motions must obey Hartmann's Law (Bucher, 1920), wherein the acute angle wedges move inward to yield rotation axes with opposite senses of rotation (Figure 8).

The data were recorded on the field forms and then keypunched and backgrounded onto the University of Massachusetts computer system, where they existed as a raw data bank. These data were then easily accessible and operations were performed on them by preexisting computer programs devised by Pferd and Piepul. One program segregates the data by station number, fracture type, host rock, surface character, any quantitative measurement, or any combination of these;

another program segregates a certain population of data by orientation; and the last program produces plots of data points or contours any segregated population of data on the lower hemisphere of an equal-area net (Piepul, 1975).

Joint Sampling Methods

As joints are numerous at outcrop scale, care must be taken to record a representative sample of the entire population. Wise (1964) lists the following pitfalls commonly met while sampling:

- 1. Horizontal joints are more commonly stepped on than measured,
- 2. A tendency exists to select the next plane for measurement subparallel with the last one measured,
- Fractures parallel with foliation or parallel to the outcrop face are more likely to be missed than those at sharp angles,
- 4. Linear traverses tend to ignore fractures parallel to them.

In addition, care must be taken when working at roadcuts not to measure blast fractures. These are recognizable as zones of vertical, radially symmetric joints.

With these potential biases in mind, the orientations of approximately 100 joints are measured at each station, a natural or artificial exposure of adequate size. In general, horizontal or subhorizontal fractures are not measured since these are commonly subparallel to bedding or may be related to sheeting in massive rocks. The size, spacing, and surface character of joints are also recorded. These data are plotted on the lower hemisphere of an equal-area net while still at the

outcrop. Joint sets which are obvious in the outcrop but not well displayed in the plot are sampled further.

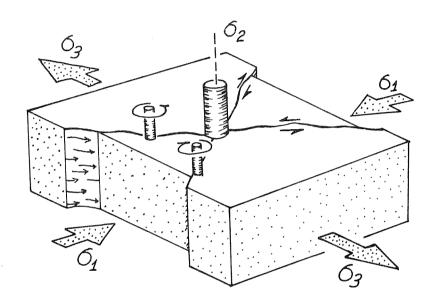


Figure 8: Block diagram illustrating relationship of conjugate faults and rotation axes (Wise, et al., 1975).

Fault Sampling Methods

In contrast to joints, which require proper sampling techniques, all faults in every exposure studied are measured. Several measurements are made for each fault: the azimuth with the plane dipping to the right, dip of the fault surface, the trend and plunge of slickensides, the trend and plunge of the rotation axis, and the down-plunge

rotation sense of the rotation axis when determinable. The rotation sense is generally determined from the character of the slickensides, confirmed where possible by stratigraphic offset and drag or drape structures. Where multiple slickensides are present on a fault surface, all slickensides are measured and an attempt is made to determine relative age relationships. Other data, such as size and displacement, are recorded for faults where observable. When sampling is complete, the data are plotted on the lower hemisphere of an equalarea net and a preliminary interpretation is attempted before leaving the outcrop. Fault patterns in the study area commonly make little sense when considered only for a single outcrop, so that computer combinations of the data are necessary, as will be discussed in a later section.

JOINTING

Method of Study

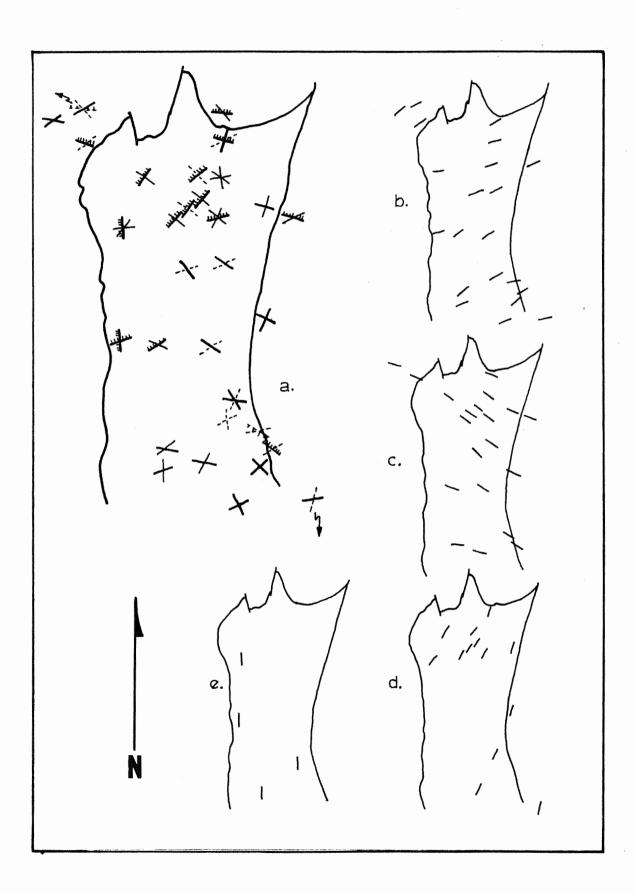
At large outcrops, the orientation, size, surface features, and mineralization (where present) of approximately 100 joints were noted on coded field forms as previously described. Orientations of all joints at each fracture station have been contoured on the lower hemisphere of an equal-area net and these data are included in Appendix I. Also shown are the locations of each station, as well as a description of each location.

Regional Patterns

It is customary to look for regional patterns in joint statistics. Strikes of joint sets at each station are shown in Figure 9a. No clear-cut patterns are present across the entire map. Dominant orientations of joint sets are separated in Figures 9b-d and are shown at their locations in the Montague Basin. A N65-75E set is widespread. A N70-80W set is also widespread but best developed in the northern basin. A N30E set is also best developed in the northern basin and along the eastern margin. A minor north-south striking set is localized along the western and southern margins of the Montague Basin.

A composite of all data is shown in Figure 10. Centers of maxima greater than 4% per 1% area on contoured plots of poles to joints at 32 individual fracture stations are shown in Figure 11a. These data have been converted into windrose and histogram form by computer and are shown in Figure 10b and c. Although the concentrations are

Figure 9: Maps showing strike of joint sets in the Montague Basin.
a) Strikes of all joint sets; heavy line represents well-defined joint set; light line represents moderately defined joint set; dashed line represents poorly defined joint set. Hachures indicate a set which dips toward the hachured side of the line. b) Locations of N65E-striking joint sets. c) Locations of N70-85W-striking joint sets. d) Locations of N30E-striking joint sets. e) Locations of N-S-striking joint sets.



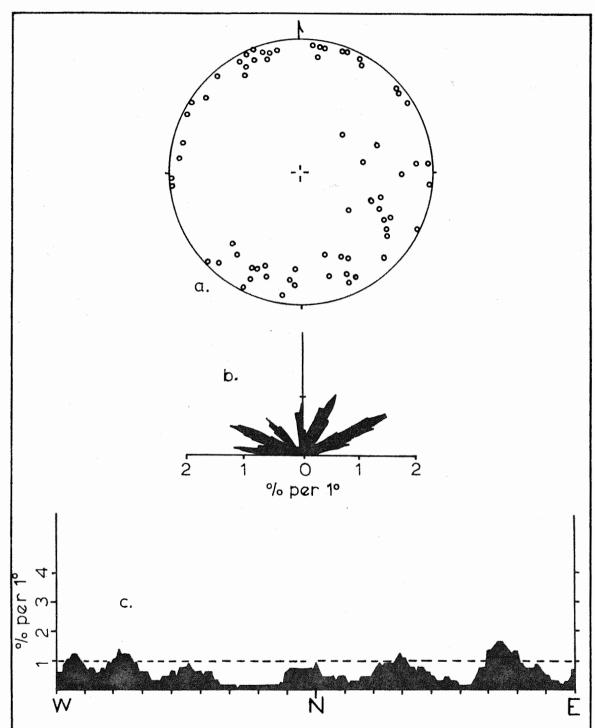


Figure 10. Composite plots of all joint data. a) 67 centers of maxima greater than 4% per 1% area from contoured plots of poles to joints at 32 individual joint stations plotted on the lower hemisphere of an equal-area net. b) Strikes of these data averaged over a 10° interval for every degree and converted into windrose form. c) Data from (b) converted into histogram form.

low, some patterns are well displayed. The strongest trends are N65E, N30E, N68W, and N85W. The northwest trends, although shown as individual maxima, are believed to represent uneven sampling of a single varied joint set since they are never seen to intersect in outcrop (Nickelsen and Hough, 1967). They also may represent two domains having slightly different orientations of this joint set (Figure 9c). The N30E trend is developed primarily in the northern basin, as previously discussed, whereas the N65E and N70-85W sets are believed to be aspects of the regional pattern.

Patterns within Subareas

The study area has been arbitrarily divided into subareas based on the orientation of bedding. These subareas serve only as a convenient way to view the data and may not have any geological significance.

Data for each subarea are shown in Figure 11, and characteristics of each subarea are shown in Table 1. Well-defined patterns similar to those discussed above exist in all subareas other than the southernmost Mount Toby/Mount Sugarloaf area.

Eastern basement area. The joint pattern in this area consists of a well-defined, near-orthogonal pair of joint sets oriented N30E and N70W. A third set which is not associated with these others is oriented N75E. Onasch (1973) and Laird (1974) also report the near-orthogonal pair from the same area (Figure 12). Ashenden (per. comm., 1975) reports this pair from the Northfield, Massachusetts, area northeast of the study area. He believes that this pattern may be

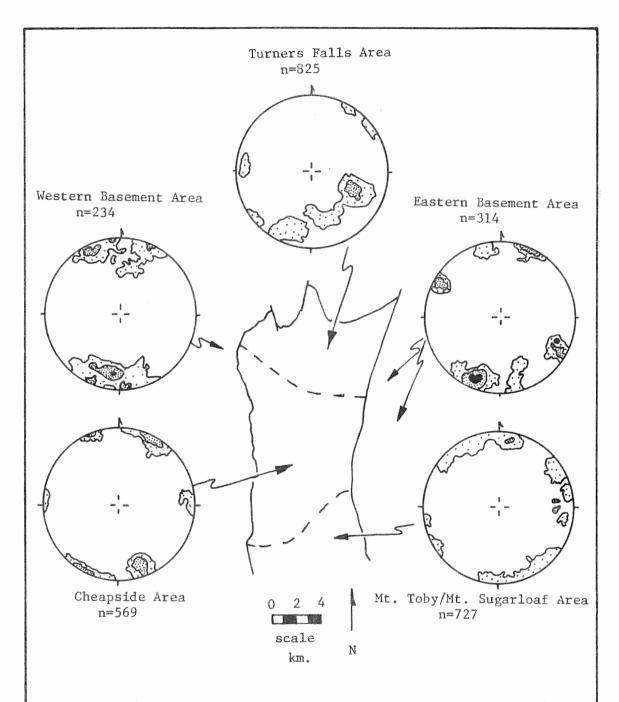


Figure 11. Joint data from subareas in the study area contoured on the lower hemisphere of equal-area nets. Contours are 2%, 4% and 8% per 1% area.

TABLE I
CHARACTERISTICS OF SUBAREAS

NAME	LOCATION	STRIKE AND DIP OF BEDDING	NO. OF STATIONS	STRIKE	OF PROMI	NENT JOINT	r sets
EASTERN BASEMENT	EAST OF BASIN	VARIABLE	3	N30E	N75E	N70W	
TURNERS FALLS AREA	NORTHERN BASIN	N60E, 30-60SE	9	N30E	N82E	N63W	N37W, N5E
CHEAPSIDE AREA	CENTRAL BASIN	N-S, 30E	6	_	N67E	N60W	N-S
MT. TOBY/ MT. SUGARLOAF AREA	SOUTHERN BASIN	N20-40W, 10-20NE	8	N10E	N45E	to N80W	N10-45W
WESTERN BASEMENT	WEST OF BASIN	VARIABLE	3		N61E	N83W	

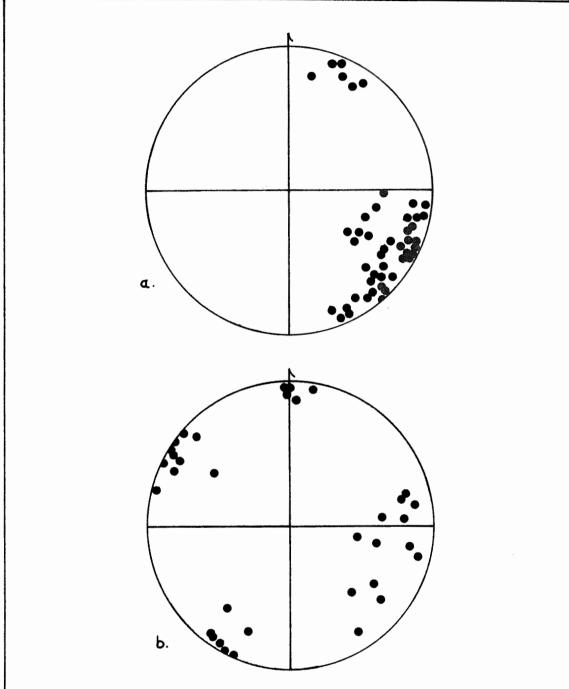


Figure 12. Joint data from other workers east of the Montague Basin. a) Poles to joints from Onasch (1973), near Millers Falls, Massachusetts. b) Poles to joints from Laird (1974), near Montague, Massachusetts.

localized along a narrow 1-to 2-mile-wide strip paralleling the border fault, but may break down eastward to more complicated joint patterns.

Turners Falls Area. The only other area in which the N30E set is well developed is in the Turners Falls area. Two other sets of joints in this area also trend approximately N75W and N75E, representing the regional pattern. Although contours of the N75E set on Figure 11 appear to encircle the N30E set, individual station plots (Appendix Ia) show that these are two distinct sets.

There is a tendency for individual locations to display near-orthogonal pairs of joint sets, one of which is commonly displayed on a regional scale. This makes an analysis of regional patterns confusing because the other set, usually oriented N30E in the Turners Falls area, appears not to have regional significance.

Joint sets in this area appear to have been systematically tilted with bedding. Price (1966) has stated that "many joints, especially in horizontally bedded series, are vertical or near vertical fractures." In the Turners Falls area joint sets which strike at a low angle to the strike of bedding are perpendicular to bedding. They, or the weakness directions they follow, appear to have formed before bedding was tilted.

Cheapside Area. The N30E set of joints which is so well developed near Turners Falls is nearly absent in the Cheapside area (Appendix Ib, Figure 9). The N70W set of joints, which appears to be its partner in other subareas, is well developed, as is the N65-75E set of joints. A minor N-S trend is seen.

Some joint sets in this subarea appear to have been tilted with bedding, while others appear not to have been. Sets which are tilted in one location are vertical in others.

Mt. Toby/Mt. Sugarloaf area. Joint sets in this area do not correspond to the regional patterns very well. Some regionally significant trends are seen, but others, such as the N45E-N45W orthogonal pairs at stations 30 and 31 (Appendix Ic), do not appear in other areas. The N70-80W trend is the only regionally significant one which is well developed in this area. Others appear to have local significance only.

The western basement area. Joints west of the basin (Appendix Id) in the Colrain, Massachusetts, area reflect the regional pattern well. The N30E set is missing, but the N65E and N75W sets are well developed. Pferd (per. comm., 1973), who assisted with the fracture analysis of this area, reports the presence of these two sets throughout the Colrain region.

Relationship of Jointing in Sedimentary Rocks to Jointing in Crystalline Rocks

Figure 11 shows that jointing in the sedimentary rocks is similar to jointing in the crystalline rocks on either side of the basin.

To examine this relationship in a more detailed manner, jointing immediately below the Mesozoic unconformity was examined at two locations. One is in the northern portion of the basin east of Bernardston, Massachusetts, and the other is on the east face of Mount Toby in a stream valley just west of the border fault. Data for these two locations are shown in Figure 13. Although some similarities exist

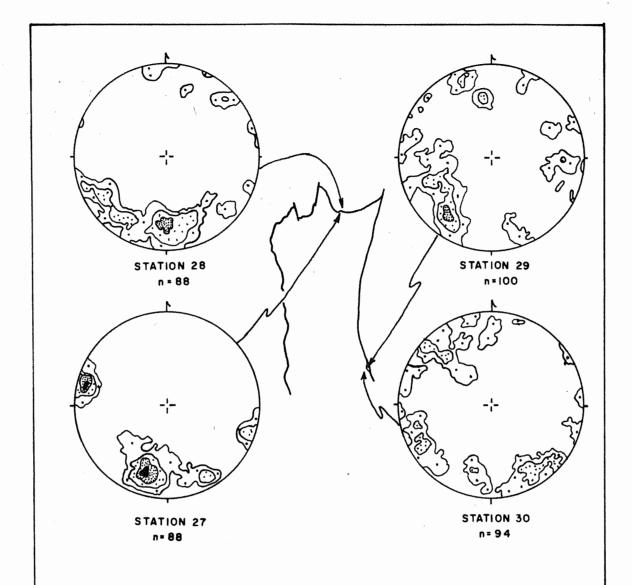


Figure 13. Jointing immediately above and immediately below the Mesozoic unconformity. Data are contoured on the lower hemisphere of equal-area nets. Contours are 2%, 4%, and 8% per 1% area.

between jointing above and below the unconformity, there are also major differences. The patterns in the cover rocks are simpler and better defined than in the basement rocks. It is very interesting to compare the patterns in the sedimentary rocks at stations 27 and 30 (Figure 13). Station 27 displays a clear orthogonal pair of joint sets oriented N70W and N20E, plus a minor maximum at N60E. Elements of all three of these sets are developed at Station 30, plus one more. The N60E set is well developed with an apparent orthogonal partner at N3OW. The basement rocks adjacent to both stations do not display this relationship. Wise (1964) has demonstrated that the basement rocks of Montana and Wyoming have a "memory" of past tectonic events in that they may have 6 to 8 preferred weakness directions and will break along one of these rather than along a new direction. A similar anisotropy may be responsible for the more complex joint patterns in the older rocks.

Separations of Classes of Joints

For each subarea, all macrojoints (very large, highly planar joints), all small joints (less than 2 meters length in outcrop), all smooth joints, and all rough joints have been separated and contoured on the lower hemisphere of equal-area nets. In addition, all joints in these four classes have been separated and contoured for the entire study area. These data are presented in Appendix II.

Total plots for all classes of joints (Appendix IIa) display the regional pattern well, especially the macrojoints and the rough joints. It is interesting to note that the N30E set which occurs

locally in the Turners Falls area is reflected only in the smooth joints.

The following observations are made based on the data shown in Appendix IIb through IIf.

Turners Falls area.

- 1. Macrojoints do not strongly reflect the N30E set of joints.
- 2. The N75W set of joints is best displayed by the rough joints.

Cheapside area.

1. All classes of joints show a similar pattern.

Mt. Toby/Mt. Sugarloaf area.

1. All classes of joints show a similar pattern.

Western basement area.

1. All classes of joints show a similar pattern.

Eastern basement area.

1. Small joints are more complex than all other classes.

Joints measured in each stratigraphic unit have also been separated.

These data are presented in Appendix IIg through IIi. Conclusions

are:

- The plot of data from the Turners Falls Sandstone reflects the N30E trend most strongly due to greater exposure, greater stratigraphic thickness, and, therefore, greater sampling in the Turners Falls area where this joint set is well developed.
- The Sugarloaf Arkose shows the regional pattern more clearly in all classes than do other lithologies.

Correlations with Other Workers

Other workers have examined joint patterns in other key parts of the Connecticut Valley. Naso (unpub. M.S. special problem, Univ. of Massachusetts, 1975) examined fracture patterns in the Holyoke Range of Massachusetts. This area has a position in the Hartford Basin similar to the position of the Turners Falls area in the Montague Basin. Naso showed that, like the Turners Falls area, this region is dominated by a set of joints oriented N30E. These, however, do not appear to be tilted. Piepul (1975) has described in detail fractures in cover and basement rocks at the southern end of the Connecticut Valley Basin near New Haven, Connecticut. He finds complex joint patterns in his study area, but shows that microjoints and headings (vertical zones of closely spaced joints) have more constant orientations than other fracture elements. One major orientation of both of these freacture types is N75E. This corresponds well with a dominant set of joints in the Montague Basin area. Thus, elements of the joint pattern from this study may be present in other parts of the Connecticut Valley Basin.

Conclusions of Joint Study

- A regional pattern of jointing may exist in the Montague Basin. It is composed of two possibly unrelated joint sets oriented N65E and N70-80W.
- This pattern exists both within the cover rocks of the Montague Basin and within the basement rocks both east and west of the basin.

- 3. The Turners Falls area is unique in two respects:
 - a) It is dominated by a N30E set of joints which appears only locally in other areas of the basin.
 - b) Joints within the area are systematically tilted with bedding.
- 4. Although similar patterns exist in the jointing of the sedimentary rocks and the crystalline rocks, detailed studies reveal that jointing in the sedimentary rocks is simpler and better defined than that in the crystalline rocks. Some joint sets in the sedimentary rocks do not appear at all in the crystalline rocks immediately adjacent.
- 5. Separations of joint classes based on size and surface character of joints generally do not show different patterns in this area. However, the N3OE joints in the Turners Falls area are characteristically smooth.
- 6. In areas of the basin other than Turners Falls, some joint sets are tilted with bedding whereas others are not.

Speculations on Significance of Joint Patterns

Speculations regarding the significance of joint patterns are severely hampered by the lack of a mechanical interpretation of joints. It is uncertain whether these features are compressional, extensional, or torsional features or are inherited from older rocks. All of the proposed theories for the origin of joints can be criticized from one point or another (Price, 1966). Price (1966, 1974) has suggested

a theory for joint formation in sedimentary rocks based on one complete tectonic cycle, i.e., sedimentation, burial, uplift. This does not appear to be applicable to the Montague Basin in that patterns in the crystalline rocks surrounding the Montague Basin are similar to those within the basin. The mechanical interpretation of these patterns is left to future workers.

The Turners Falls area is unique in its jointing. Whatever the mechanical origin of the joints, the N30E set of joints is largely restricted to this area. The relative age of these joints with respect to other joints cannot be determined, but they are believed to have formed with a late phase of basin development in that they appear to be related to drape folds discussed in a later section.

They are tilted and hence predate tilting. In other parts of the basin, some sets of joints have been tilted and others have not. It follows that multiple periods of joint formation have spanned at least one period of tilting. However, there does not appear to be any preference for which sets have been tilted and which are vertical.

FAULT ANALYSIS

Introduction

Detailed analyses of minor fault motions are not common in the literature. None could be found which presented data on minor faults, determined the patterns, and interpreted those patterns from a mechanical or tectonic viewpoint. The most similar paper to the present analysis is Donath's (1962) "Analysis of Basin-Range-Structure, South-Central Oregon," in which he clearly presents several of the basic principles behind a regional fault analysis.

Faults bear a simple geometric relationship to the stresses under which they form in an isotropic medium. Shear fractures formed in such a medium ideally occur in conjugate pairs, the acute angle of which is bisected by the maximum principal stress (σ_1) . Thus, given the orientation of a stress system, one may predict the approximate orientation of the conjugate fractures which might form in an isotropic material under that stress system. Conversely, given a conjugate fracture system and its motion senses, one may deduce the orientation of the causal stresses.

Fault Occurrence

Although minor faults are present in every stratigraphic unit of the basin, they are most prevalent in the Deerfield Diabase.

Columnar jointing is not common in this unit. It is homogeneous and is the most brittle unit of the Montague Basin.

Fault Pattern within the Basin

When data for all faults in the Montague Basin are examined, a

clear pattern emerges. There is a preferred orientation of faults ranging in strike from N80E to N20W, with an average orientation of N55E 50NW (Figure 14a). A minor preferred orientation which will be shown to have significance occurs at N60W 60SW. Despite the preferred orientation of faults within the basin, a variety of motions have occurred on the faults. Rotation axes (Figure 14b) show various orientations and fall on a partial great circle corresponding approximately to the preferred orientation of fault planes. This indicates that dip-slip, strike-slip, and oblique-slip motions all have occurred on these faults.

Determination of the type of motion on a fault from its rotation axis is based on an approximation of the rake of that lineation in the fault plane. Faults with slickensides having a rake from 0° to 30° are considered strike-slip, those having a rake from 31° to 60° are considered oblique-slip, and those having a rake from 61° to 90° are considered dip-slip. Examination of the rake of all slickensides in their fault planes shows that all three types of motions are prevalent in the basin (Figure 14c).

All rotation axes with a known clockwise rotation sense (Figure 15a) and counterclockwise rotation sense (Figure 16a) have been segregated with their corresponding fault planes (Figures 15b and 16b respectively.) The poles to those faults with clockwise rotation axes (Figure 15b) show a bimodal distribution. Separation of each cluster in Figure 15b with their respective rotation axes shows three elements of the fault pattern. Northeast-striking northwest-dipping fault

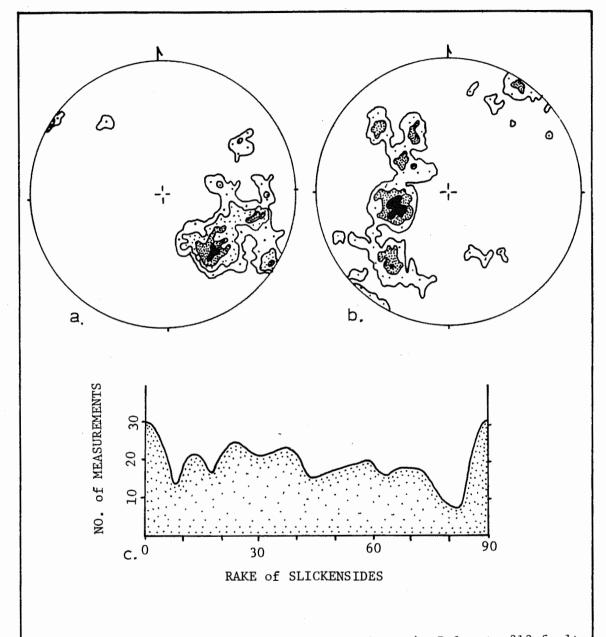


Figure 14. Fault data in the Montague Basin. a) Poles to 313 faults observed in the study area contoured on the lower hemisphere of an equal-area net. Contours are 2%, 3%, 4%, and 5% per 1% area. b) 327 rotation axes measured in the study area contoured on the lower hemisphere of an equal-net area. Contours are 2%, 3%, and 4% per 1% area. c) Rakes of 327 slickensides measured in the study area plotted on a histogram.

Figure 15. Analysis of faults having clockwise rotation axes.

a) 50 rotation axes with a known clockwise rotation sense when viewed down the plunge plotted on the lower hemisphere of an equal-area net. b) 50 poles to faults on which they were measured contoured on the lower hemisphere of an equal-area net. c) separation of data from (a) and (b) showing northeast-striking northwest-dipping faults and corresponding rotation axes. d) separation of data from (a) and (b) showing northwest-dipping faults and corresponding rotation axes.

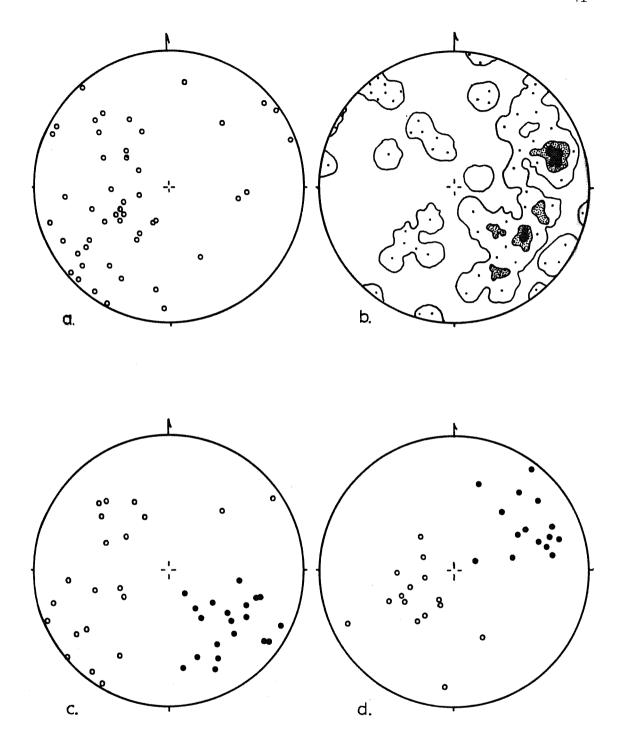
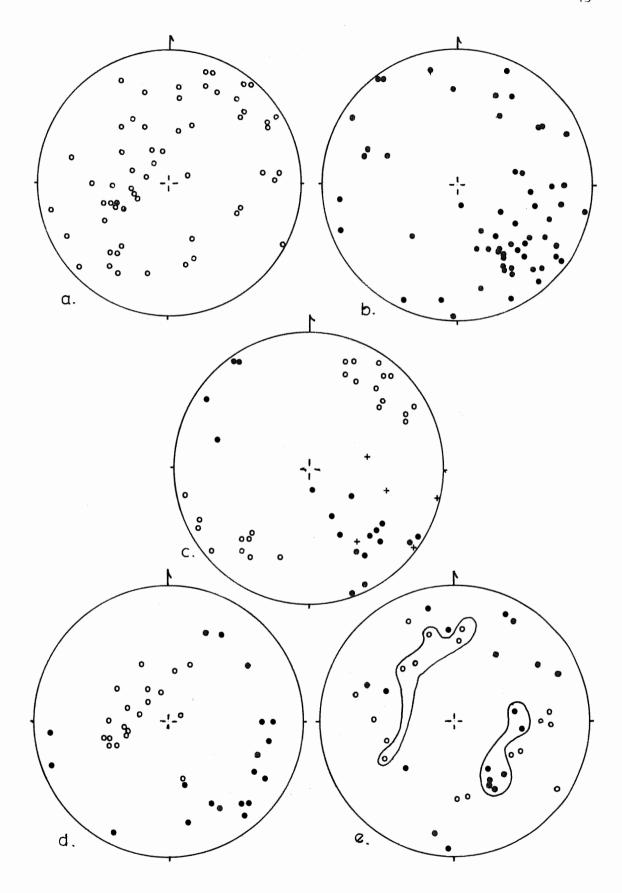


Figure 16. Analysis of faults having counterclockwise rotation axes. a) 60 rotation axes with a known counterclockwise rotation sense when viewed down plunge. b) 57 poles to faults corresponding to those rotation axes. c) separation of northeast-trending rotation axes plunging less than 45°, and corresponding poles to faults. d) separation of all rotation axes plunging greater than 45°, and corresponding poles to faults. e) all other rotation axes and corresponding poles to faults. A family of northeast-striking northwest-dipping fault planes and their corresponding rotation axes showing left-lateral strike-slip motion is circled.

- o rotation axis
- - pole to fault
- + pole to reverse fault



planes have right-lateral motions and normal motions with a right-lateral component. Minor reverse faults are present (Figure 15c).

Northwest-striking southwest-dipping fault planes have only right-lateral strike-slip motions (Figure 15a).

This is half of the analysis. Additional elements of the fault patterns are shown by faults having counterclockwise rotation axes (Figure 16a-d). These faults (Figure 16b) have a strong northeast preferred orientation similar to some of the clockwise faults. Their rotation axes (Figure 16a) show complex motions. Segregations based on orientation of rotation axes reveal (Figure 16c) a family of northeast-striking northwest-dipping normal faults with a leftlateral component and minor northeast-striking southeast-dipping normal faults and northeast-striking northwest-dipping reverse faults. The reverse faults, other than being a small population, are mostly from exposures directly below the dam at Turners Falls, have vertical extents no greater than 10-15 cm and displacements of 1-3 cm, as derived from stratigraphic offsets. The analysis also shows a family of northeast-striking northwest-dipping left-lateral faults (circled in Figure 16e) and a profusion of erratically oriented faults with various motions (Figure 16e). One interesting element among these erratically oriented faults is a group with northwest to east-west strikes and rotation axes indicating left-lateral strike-slip motion. Four of these come from Station 29, which is in the Paleozoic crystalline rocks below the Mt. Toby Conglomerate on the east flank

of Mt. Toby. They have no real counterpart in faults of Juro-Triassic rocks. Another interesting element includes faults striking northwest with motions down on the southwest and with a right-lateral component. These come from within the Falls River gorge where it enters the Connecticut River at Turners Falls. These may well be secondary effects of the Falls River fault which occupies the gorge. Figure 16c shows the remaining elements of the fault pattern, a set of northeast-striking northwest-dipping left-lateral faults. Again, the northwest-striking left-lateral faults come primarily from Station 29 on the east side of Mt. Toby.

One other set of faults occurs in the area although no data were obtained. These are well displayed at the contact of the Sugarloaf Arkose with the Deerfield Diabase on the cliff immediately east of the pond at Highland Park in the town of Greenfield, Massachusetts. These faults are thrusts striking approximately east-west, with the north side displaced over the south side. They are localized at the contact and turn upwards sharply to cut through the entire section of exposed Deerfield Diabase. Displacements of the contact are on the order of several feet (1-1.5 meters) vertically, indicating true horizontal displacements of much greater magnitude. Figure 17 illustrates the relationships diagrammatically.

The orientations of the major fault sets of the basin are summarized in Figure 18. The pattern is dominated by a set of faults oriented N55E 50NW with right-lateral, left-lateral, and normal motions, and a N30W 70SW set with exclusively right-lateral motions.

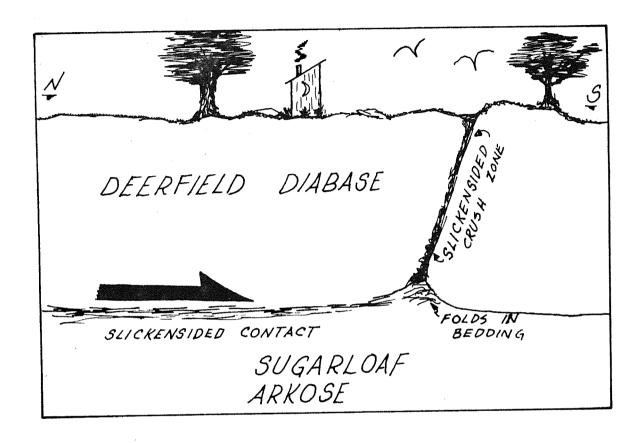


Figure 17. Diagrammatic sketch of cliff near Mountain Park, Greenfield, showing thrusting along lower contact of Deerfield Diabase.

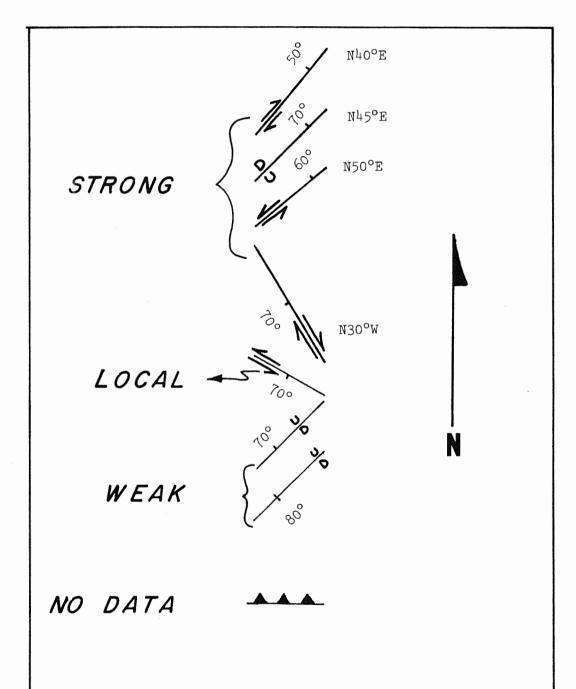


Figure 18. Summary of fault set orientations and motions in the Montague Basin.

Minor elements include a N60W 70SW set of right-lateral faults displayed at one locality in the crystalline basement and minor northeast-striking dip-slip faults with various dips. The observed thrust faults along the base of the Deerfield Diabase have been included in the figure.

It is believed that the northeast and northwest strike-slip faults represent a conjugate pair. At several locations their rotation axes are coincident and normal to bedding, indicating that the σ_2 orientations for both sets are similar. The dihedral angle between the two sets is from 50 to 65 degrees. With the exception of right-lateral motions on some of the northeast faults, relative motion senses on the two sets agree with Hartmann's Law with the acute angle wedge between the two sets moving inward. However, field relationships have not been found which show simultaneity, the final condition to prove a conjugate relationship.

Fault Patterns in Subareas

Data from two areas within the basin have been segregated and analyzed separately. The area surrounding Turners Falls, Massachusetts, has received much attention in the field work. A total of 194 of the 278 faults measured within the Montague Basin come from that area. The other 84 are located in and near the Cheapside Quarry in Deerfield, Massachusetts (refer to index map Appendix I for locations of sampling localities). The two areas appear to be in geologically different environments. The Turners Falls area displays numerous large faults and has an average bedding orientation of

approximately N60E 40SE, whereas the Cheapside area lacks large faults and has an average bedding orientation of approximately N-S 30E. It is possible that the larger number of fault measurements at Turners Falls has biased the fault analysis. We wish to know if the fault patterns in the two separate areas of the basin are the same or different. This requires determining or inferring the relative ages of faulting and tilting. If the area was uniformly faulted first and then tilted to different strikes along different axes, orientations of fault sets in the two areas should be different. When bedding is rotated to horizontal on an equal-area net and fault planes are rotated in a similar manner, the fault patterns should coincide. If the basin has been tilted first and then uniformly faulted, patterns in the two areas should be similar without any rotation of the data. Results of this analysis are discussed later.

Geographic distribution of mapped faults. Most mapped faults occur along the northeast arm of the basin, in the Turners Falls region. This may be due to several factors:

- 1. Large-displacement faults may simply be more prevalent in that area than in the rest of the basin.
- Bedding in this area strikes at a higher angle to the dominant NNE strike of most faults, making their presence easier to detect. Faults parallel to bedding will seldom be seen by stratigraphic offset.
- 3. The stratigraphic marker, the Deerfield Diabase, has a greater topographic expression in this area, making stratigraphic offsets easier to detect.

4. Exposure of contacts in this area is very good, due to structural control of topography and drainage. Best exposure is along the bed of the Connecticut River, near the town of Turners Falls, at the upper contact of the Deerfield Diabase. Seasonally, the river is diverted for hydroelectric power exposing the contact.

An analysis of minor faults might show if this local occurrence of large faults is real or apparent.

The Cheapside area. Orientations of 84 small-displacement faults have been measured in and around the Warner Brother's Quarry at Cheapside in the town of Deerfield, Massachusetts. The pattern of faults in this area is relatively simple. Faults oriented N3OE 55NW show both right- and left-lateral motions. Faults oriented N3OW 60SW show almost exclusively right-lateral motions (Figure 19). Dip-slip faults are rare. The pattern is summarized in Figure 20.

The Turners Falls area. The pattern of faulting in the Turners Falls area is more complex (Figure 19). Northwest faults, not common in this area, show dominantly right-lateral motions as they do in the Cheapside area. Northeast faults also are similar to those at Cheapside in that they display both right- and left-lateral motions. The major difference between the two areas is the strong presence of dip-slip faults striking northeast at Turners Falls. These commonly have a right-lateral component of motion. In the Cheapside area they are nearly absent. The fault pattern at Turners Falls is summarized in Figure 20.

Histograms of rake of slickensides in the two subareas
(Figure 21) show the differences. Both areas have an abundance of

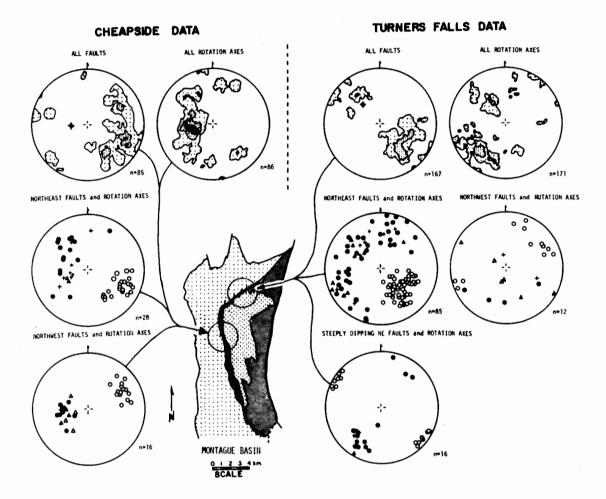


Figure 19. Fault data at Cheapside and Turners Falls, Massachusetts, contoured on the lower hemisphere of equal-nets. Contours are 2%, 4%, and 10% per 1% area. Sets of faults at both areas are plotted separately on equal-area nets.

- → average pole to bedding
- O pole to fault plane
- - rotation axis, sense unknown
- Δ clockwise rotation axis
- + counterclockwise rotation axis

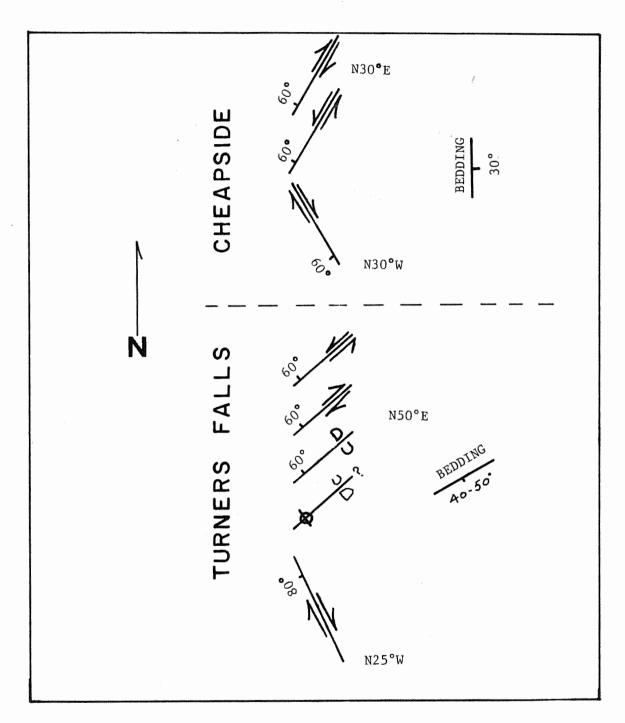


Figure 20. Diagram of fault set orientations and motions at two subareas in the Montague Basin.

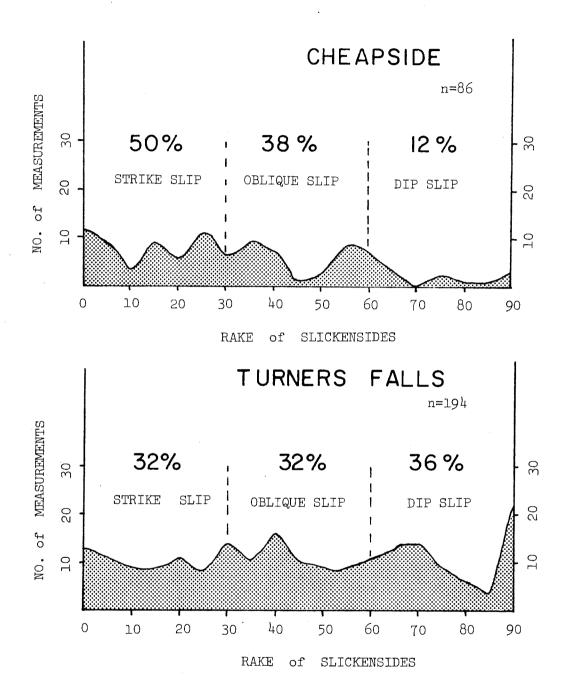


Figure 21. Histograms of rakes of slickensides at two subareas in the Montague Basin.

strike- and oblique-slip faults whereas the Turners Falls area alone displays large numbers of dip-slip faults.

Orientations of fault sets. No valid statistical method exists to define the mean orientation of an arbitrarily segregated set of data distributed on a sphere. Thus, approximate mean orientations of fault sets have either been chosen as the center of a maximum or estimated by eye. The dispersion of data about these approximate mean orientations may be large, and overlap exists between sets. The raw data are shown in Figure 19.

The orientations of both the northeast and the northwest sets of faults vary between the two subareas (Figure 20). The orientations are summaried below in Table 2. The sets at Turners Falls have strikes $10-20^{\circ}$ clockwise with respect to those at Cheapside.

TABLE 2. ORIENTATIONS OF FAULT SETS AT TWO SUBAREAS

P- 15	Orientation at		True Angular
Fault set	Cheapside	Turners Falls	Difference
Northeast	N30E 62NW	N50E 50NW	22
Northwest	N30W 64SW	N20W 80 SW	16
Dihedral Angle	50	65	

Summary of Fault Patterns

1. Faults striking predominantly N30-50E and dipping approximately 50NW dominate the fault pattern.

- 2. These faults have experienced both right- and left-lateral strike- and oblique-slip motions.
- 3. In the Turners Falls area they have also experienced dipslip motions predominantly down on the northwest.
- 4. Faults oriented N30-45W and dipping 60 to 70SW are not as common, but locally form a distinct set. They have experienced almost exclusively right-lateral strike-slip motions.
- 5. Orientations of fault sets in two geologically different subareas of the basin are not the same.

Fault Related Structures: Folds

Extensive exposures below the dam at the town of Turners Falls,

Massachusetts, display a large thickness of the lowermost Turners Falls

Sandstone and uppermost Deerfield Diabase. These exposures also

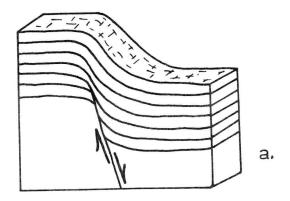
contain numerous faults in both the volcanic and sedimentary rocks,

and several folds. Some of the folds are isoclinal recumbent "soft

sediment" folds overturned toward the northwest, whereas others are

drape folds over faults.

Some faults in the Turners Falls Sandstone die out up section into asymmetric folds of several centimeters amplitude and give an indication of the relative movement on the fault. Other larger drape folds of several meters amplitude occur in the sandstone over faults in the Deerfield Diabase. These folds are also asymmetric and give an indication of the relative movement on the fault. Their monoclinelike nature is shown in Figure 22a. Figure 22b is a photograph of



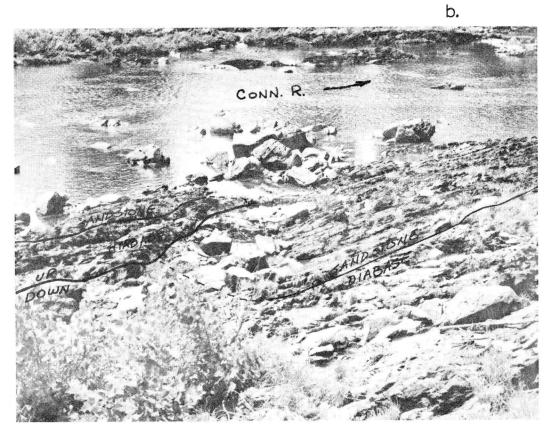


Figure 22. a) Block diagram showing ideal drape fold.
b) Photograph of large drape fold and fault at
Turners Falls, Massachusetts (Location #1 in
Figure 23).

a large fold with the exposed fault beneath. Low altitude vertical air photographs of the area revealed several linears cutting the section. Field checking showed that these are either folds having clockwise rotations similar to the drape folds, or zones of contorted bedding related to drape folds. The locations of several prominent fold zones are shown in Figure 23. Air photographs of the folds are shown in Figures 24, 25 and 26.

Figure 24 is an air photo of the fold shown in Figure 22.

The fault associated with the large fold strikes N20-30E and dips
70 to 80NW. Two other folds are shown with more easterly trends.

No faults could be seen associated with them, although they are interpreted as having fault-related origins.

Figure 25 shows a zone of folds, disturbed zones, faults, and indropped wedges above a major mapped fault (Willard, 1957), here named the Canada Hill fault. The three fold axes all trend N20-30E. On the east side of the river, on the projection of these folds, the rocks are less well exposed and so thoroughly broken that the fold pattern could not be traced.

Figure 26 shows a fault cutting a major portion of the Turners Falls Sandstone. It is a zone of disturbed bedding that hints of a clockwise rotation. Along its projection across the river is a zone of four folds, all asymmetric toward the northwest, and all trending northeast. Thus, this planar zone appears to be present 150 meters above the faulted top of the volcanic unit.

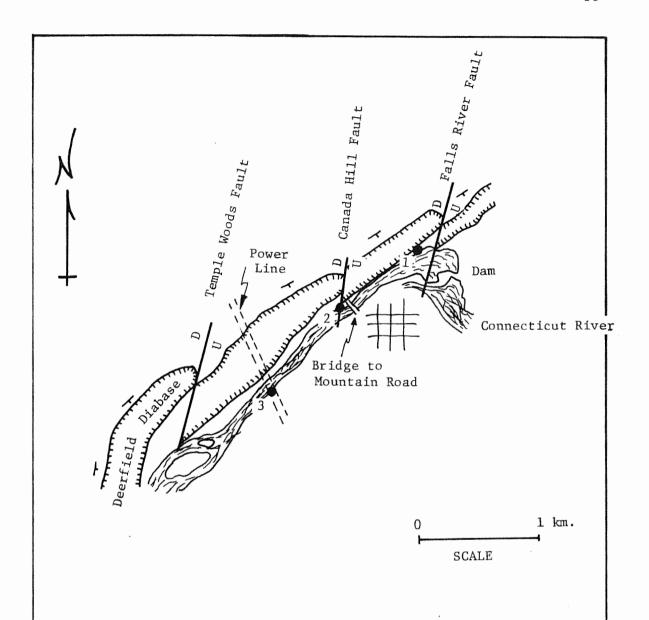


Figure 23. Sketch map of the Turners Falls, Massachusetts area showing the outcrop pattern of the Deerfield Diabase, the location of the Connecticut River, and the location of three major zones of folds studied. Location 1 is shown in Figures 22b and 24. Location 2 is shown in Figure 25. Location 3 is shown in Figure 26.

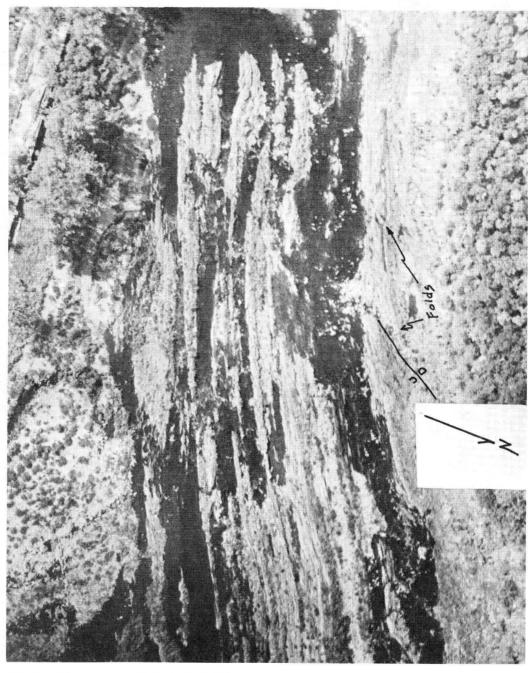


Photo Courtesy of G.E.McGill

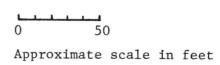


Figure 24. Air photo of fold zone #1.

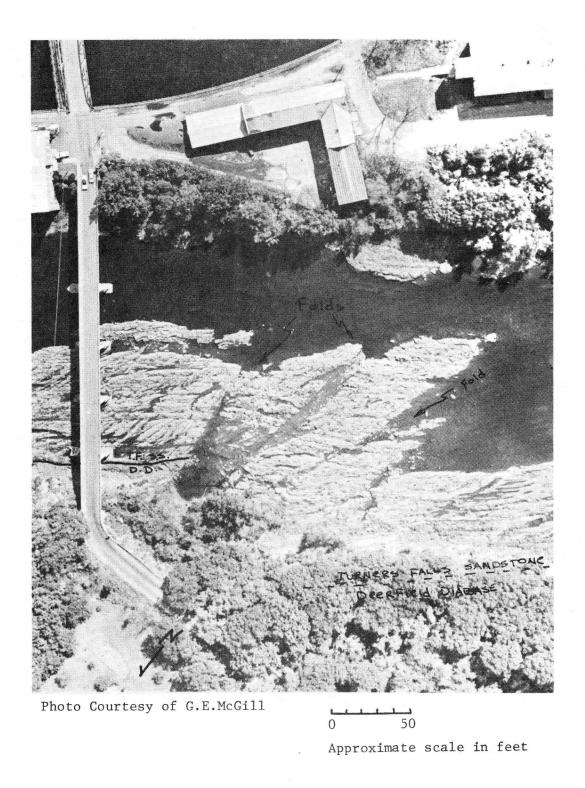


Figure 25. Air photo of fold zone #2.

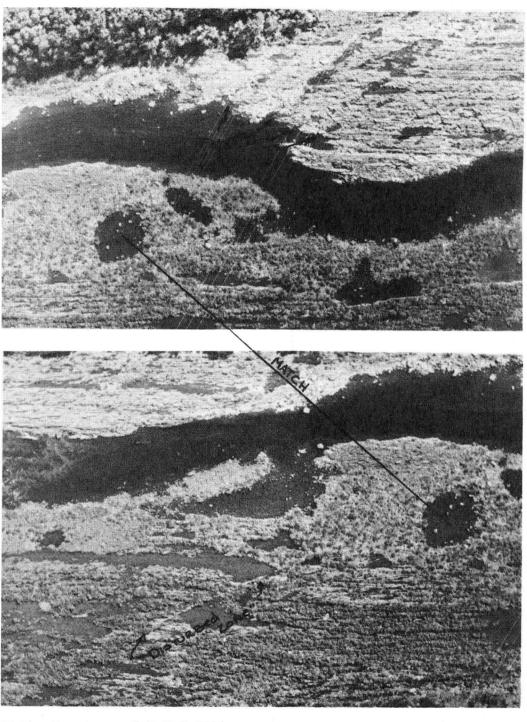


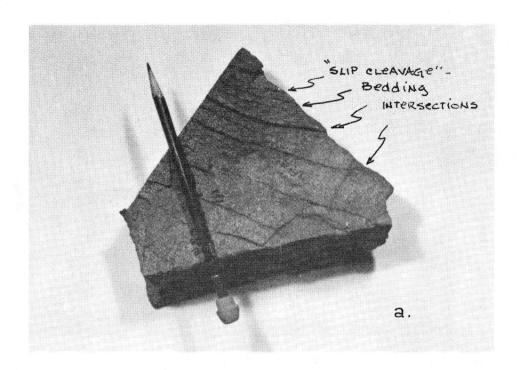
Photo Courtesy of G.E.McGill

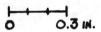
Figure 26. Air photos of fold zone #3.



Approximate scale in feet







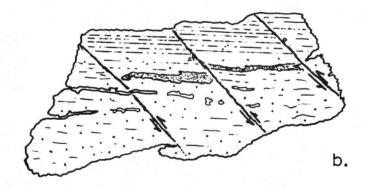


Figure 27. Hand sample and thin section of Turners Falls sandstone taken from near fold #1 (Figure 23).

a) Hand sample showing "bedding-cleavage intersections." b) Thin section cut perpendicular to bedding and "cleavage" showing "cleavage" to be microfaults.

Faults in the diabase related to these structures could not be identified due to lack of exposure.

The folds have the following general characteristics:

- 1. Of the 16 folds identified, 14 have axes trending N20-30E.
- 2. Five of the 16 folds are observed to be related to faults.
- All 14 of the N20-30E folds indicate motion down on the northwest.
- 4. The folds vary up section, decreasing in amplitude and increasing in wavelength. Some are present 150 meters above the Deerfield Diabase.
- 5. Several folds have associated with them a "slip cleavage" which creates lineations on bedding planes parallel to fold axes. In thin section, this (Figure 27) is seen to be due to microfaulting.
- 6. Within the fold zones, jointing is irregular and parallel to the axial planes and master faults. Joints are commonly open and mineralized with calcite, barite, or quartz.

Significance of Fault Pattern: Mechanisms and Timings

Boundary conditions. A distinctive fault pattern exists in the Montague Basin, a pattern that varies somewhat between two key areas in the basin. In order to examine the significance of this pattern, it is necessary to define several boundary conditions.

1. Mesozoic basic dikes in New England trend approximately
N30E. This indicates that extension was occurring along

- a N60W direction, the orientation of the minimum principal stress (σ_3) (May, 1971).
- 2. Near the earth's surface, one principal stress must be normal to the surface or near-vertical for all but alpine terrain. For homogeneous isotropic substances, the intermediate principal stress (σ_2) must lie within the fault plane (Anderson, 1951).
- 3. To develop vertical strike-slip faults, the maximum principal compression (σ_1) must be horizontal and, if conjugate faults develop in an isotropic substance, σ_1 will bisect the acute angle of intersection of those faults (Anderson, 1951).
- 4. Conjugate faults, besides having the proper geometric relationship, must have opposite senses of displacement with the acute angle wedge moving inward... Hartmann's Law (Bucher, 1920). In addition, they must have formed simultaneously.
- by fractures is subjected to a new compression, new fractures will form only when that compression is oriented at a high angle to the preexisting fractures. If the compression direction makes a small to moderate angle with those old fractures, new movement can occur on them (Donath, 1962).

Implication of the fault pattern. Except for differences in orientation and numerous normal faults within the Turners Falls area,

the pattern of faulting at Cheapside and Turners Falls is similar. If the simpler pattern at Cheapside represents the basin-wide pattern, then the complexity of the pattern at Turners Falls is due to local conditions, such as additional deformations.

The pattern at Cheapside suggests a conjugate pair of strikeslip faults. The dihedral angle of 50° is small by theoretical standards, but is within experimental limits (Handin and Hager, 1957). Except for the right-lateral motions on some of the northeast faults, fault motions obey Hartmann's Law, with the acute angle wedge between the two faults moving inward. That the northeast and northwest fault sets developed simultaneously cannot be proven. However, if one had formed before the other, the σ_1 stress orientation needed to form the second, and still give it the proper sense of displacement, would have been oriented at a low angle to the first, causing additional motions rather than allowing a new fault to form, as discussed above. Thus, contemporaneity of origin is assumed.

Tilting of fault sets. In a near-surface environment, one principal stress is vertical. When vertical strike-slip faults develop, the intermediate principal stress (σ_2) is vertical, with the maximum (σ_1) and minimum (σ_3) principal stresses horizontal (Anderson, 1951). The strike-slip faults in the Montague Basin are not vertical. They are, however, perpendicular to bedding, as are their rotation axes. When the orientation of bedding is brought to horizontal on an equal-area net, and approximate mean orientations of fault sets are rotated in a similar manner, those orientations (and the corresponding orientations of rotation axes) become

vertical. This is true for both the Cheapside and Turners Falls areas regardless of the orientation of axes used to perform this rotation. The implication is that these faults formed when bedding was horizontal.

This rotation changes the strike of fault sets as well as the dip. When the strike of bedding in the two areas is used as an axis of rotation, the orientations of the fault sets do not become coincident (Figure 28 and 30).

The horizontal compression. We already have some knowledge of the state of stress in the crust during the early and middle Mesozoic. Dikes commonly form perpendicular to the minimum principal stress (σ_3) . In New England, Mesozoic basic dikes indicate a σ_3 orientation of approximately N60W. This extension direction is presumably due to crustal stretching during rifting of North America, Europe and Africa (May, 1971). May (1971) also suggests that at this time σ_1 was horizontal. The orientation of dikes gives only the $\sigma_1\text{--}\sigma_2$ plane without distinguishing which was horizontal or which was vertical. Price (1966) has shown that to obtain strike-slip faults, a lateral compression and lateral extension must act together. Although there appears to be an origin for extension during the Mesozoic, there is no obvious geologic explanation of the horizontal compression which must have been active in the Montague Basin during strike-slip faulting.

Orientations of stress during faulting. The orientations of principal stresses necessary for strike-slip faulting at Turners

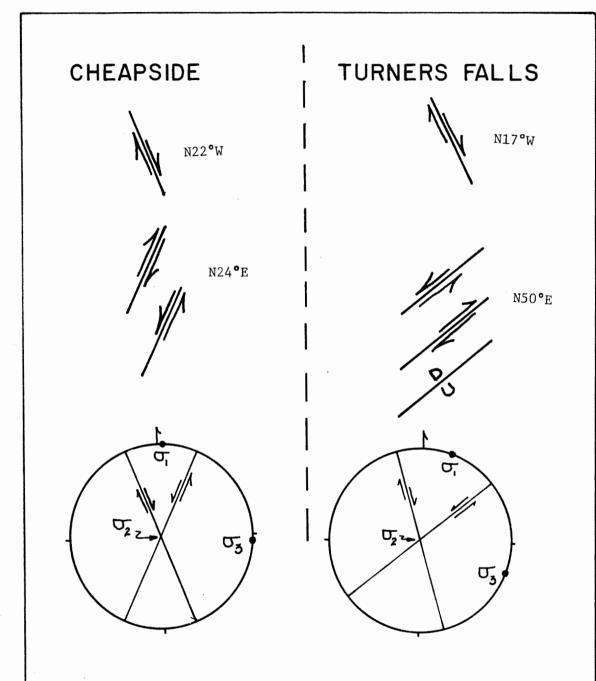


Figure 28. Orientations of fault sets and causal stresses at two areas in the Montague Basin after bedding is rotated to horizontal about its strike.

Falls and Cheapside when bedding was horizontal are shown in Figure 28. The σ_3 orientations shown do not correspond to May's (1971) crustal stresses. In addition, the orientations of σ_1 and σ_3 are not constant. There are two possible explanations for this lack of consistency. The difference in orientation from crustal stresses will be discussed in this light.

Complex tiltings. The orientations of stresses are shown for faults rotated about the strike of bedding (Figure 28). These only have significance if bedding was tilted about its present strike. Wheeler (1937) has postulated a mechanism for the formation of arcuate ranges in the other Mesozoic basins that implies a simple tilting. He believes that depressions in the plane of a basin's border fault could account for differential displacements along that fault to produce arcuate ranges. Some examples he cites are the ranges at the southern end of the Hartford Basin (Figure 2). The arcuate nature of the Montague Basin does not conform to Wheeler's suggested geometry. It is more like a sharp fold than an arc, with two planar limbs and the maximum curvature of the volcanic unit occurring in a small area near Greenfield, Massachusetts (Figure 4). For this reason, his mechanism is not believed to be primarily responsible for the form of the Montague Basin and simple tilting of the whole basin seems unlikely.

Complex tilting may account for the difference in fault-pattern orientations. It may be that the Turners Falls area, indeed, the entire northeast portion of the Montague Basin, has experienced

more than one tilting about different axes, rotating bedding and faults into orientations different from those in the rest of the basin.

If the northeast- and northwest-striking fault sets are conjugate and originally had constant orientations throughout the basin, their orientations will become coincident when the proper rotations are performed on the equal-area net. The problem lies in deciding what the orientations of the real axes of rotation were, as the results will have significance only when the rotations performed on the net correspond to the real rotations. Because the dihedral angles at Cheapside and Turners Falls are 50° and 65° respectively, it is clear that gross rotations alone will never bring the two fault patterns into perfect coincidence.

Any number of possible combinations of axes and amounts of rotation can be thought of to bring bedding to horizontal. If we limit the number of rotations to two, only a few combinations make geological sense. These possible scenarios for the tilt history of the Montague Basin are:

 After deposition of most of the stratigraphic thickness, the entire basin was first tilted eastward about a N-S to N10W horizontal axis by about 20° to 30°. This corresponds to the tilted condition of the Cheapside area. Later, the Turners Falls area was tilted about a N80W horizontal axis to its present position (Figure 29b).

- After deposition, the Turners Falls area was first tilted about a N80W horizontal axis by 20° to 30°.
 Then the entire basin was tilted about a N-S to N10W horizontal axis (Figure 29c).
- 3. After deposition, the Turners Falls area was first tilted 20° to 30° about N30E horizontal axis. Then an additional tilt of 20° to 30° about a N80W horizontal axis was imposed. The Cheapside area was simply rotated about a N-S to N10W horizontal axis to its present orientation (Figure 29d).
- 4. After deposition, the first tilt was about a N80W horizontal axis, and the second tilt was about N30E horizontal axis. The Cheapside area experienced the simple tilt as in No. 3 above (Figure 30e).

The effects on fault orientations of these four scenarios are illustrated in Figure 29. Figure 29d shows simple rotation of both the Cheapside (CS) and Turners Falls (TF) data about the strike of bedding. In Figure 29b-e the Turners Falls data are rotated as described in scenarios 1 through 4 in an attempt to bring those data into coincidence with those at Cheapside. None of these scenarios bring the fault sets into similar orientations.

Two other possible scenarios exist:

- 5. After deposition, tilts were about non-horizontal axes.
- Both areas have experienced different multiple tilts about different axes by various amounts.

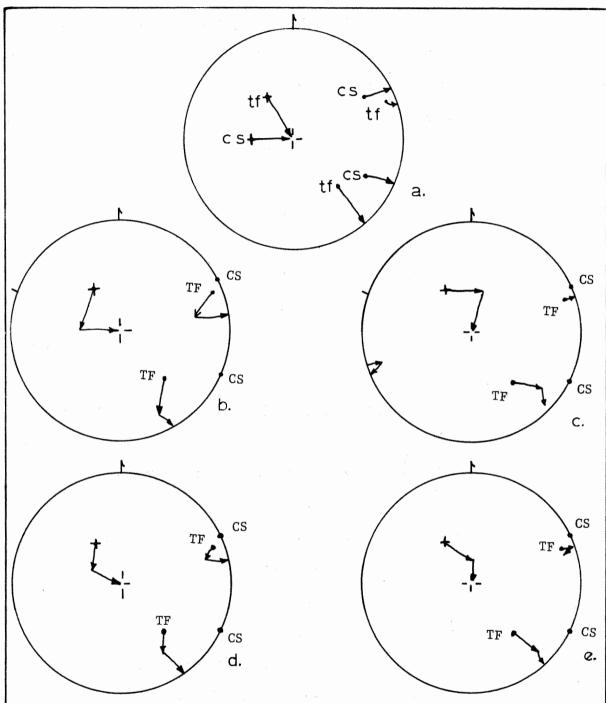


Figure 29. Possible scenarios of multiple rotations of faults and bedding at Turners Falls and Cheapside. a) Both areas rotated about strike of bedding. b-e) Turners Falls (TF) data rotated as described in text in attempts to bring them into coincidence with Cheapside (CS) data after rotation about strike of bedding.

- pole to fault set
- + pole to bedding

The complexity of these two scenarios introduces too many variables to analyze efficiently. Preliminary rotations corresponding to both of the above were performed and did not show satisfactory results.

They are not illustrated.

Yet another type of rotation is possible:

7. The Turners Falls area has been rotated 20° clockwise about a vertical axis.

Rotation such as this has occurred in the Farmington Reservoir area in the Hartford Basin (Wise, et al., 1975). Fault sets could be brought into near coincidence using this mechanism, but I find it difficult to envision the mechanism for such rotation occurring in this geologic environment.

Curving stress trajectories. If multiple rotations cannot account for the variation in fault-set orientation, it follows that stress orientations were not constant in the basin during strike-slip faulting. Hafner (1951) has shown that curving stress trajectories are theoretically reasonable. The observed curvature in the Montague Basin could be due to one or more of several causes.

1. The subsidence mechanism, whatever it may have been, could have created stresses which varied within the basin. This seems likely as very few strike-slip faults are present in the crystalline rocks east of the Montague Basin (Ashenden, per. comm., 1975) or north of the Montague Basin (Ahmad, 1975).

The border fault may have served to reorient the crustal stresses spoken of by May (1971). Anderson (1951) has shown that a perfectly lubricated surface will reorient stresses in its vicinity so that one principal stress is perpendicular to that surface. It follows that even an imperfectly lubricated surface will reorient stresses somewhat. Figure 30 shows that $\sigma_{\mathbf{q}}$ is nearly perpendicular to the curving trace of the border fault at both Cheapside and Turners Falls. fault, however, dips to the west and a stress perpendicular to that fault would plunge to the east. Also, in the near-surface environment one principal stress must be Thus the earth's surface may have been intervertical. acting with the border fault to reorient crustal stresses to the orientations shown in Figure 30.

Speculation. Although the data neither support nor reject either mechanism for curving stresses, I find the subsidence origin of stresses to be least objectionable. The second, reorientation of crustal stresses, seems contrived and does not truly account for the observed features. The exact mechanism to produce stresses by basin subsidence is not known. One reason is that the subsidence mechanism is also unknown. Detailed fault analysis in the southern Montague Basin might prove or disprove this hypothesis.

The previous models only account for left-lateral motions on northeast-striking faults. The origin of right-lateral motions is

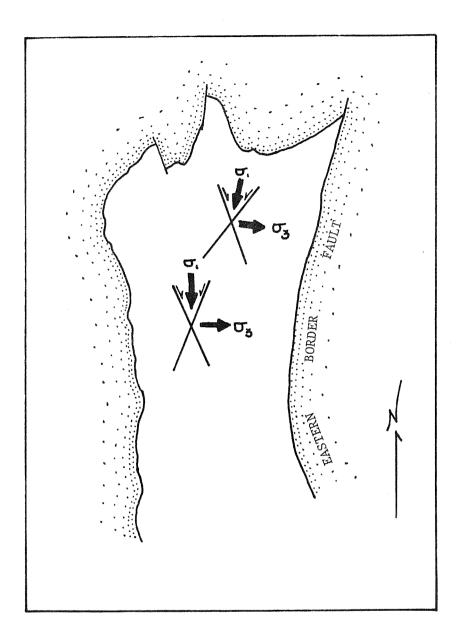


Figure 30. Horizontal stress directions at two areas in the Montague Basin after rotation about the strike of bedding.

uncertain. A σ_1 stress oriented more easterly than the northeast faults would impose right-lateral motions on them. In addition, this east-northeast-oriented stress would impose a high component of normal stress on northwest faults, tending to lock them. The possible tectonic cause of this hypothetical stress is unknown, but it may be related to basin subsidence and tilting.

Normal faults oriented N50E 50NW are present only in the Turners Falls area. They are parallel to northeast strike-slip and oblique-slip faults. They are closely associated with the folds described previously. They are believed to have formed late in the fault history of the basin by additional rotations of the northern portion of the basin. Although the cause and mechanisms of this tilting are uncertain, its presence would account nicely for the observed pattern. A possible mechanism is illustrated in Figure 31. Although simple multiple tilting at Turners Falls does not account for variations in fault-set orientations, the complexity of curvature and faulting in that area suggests that multiple tilting is a major component of the kinematic development.

This local occurrence of small normal faults and large mapped faults with similar strikes is highly suggestive. One large fault has associated dip-slip drape folds similar to those associated with smaller faults. It follows that the large faults are probably normal. They are believed to be present in the Turners Falls area due to its position in the basin. These normal faults may be related to basement structures, as suggested by Willard (1952).

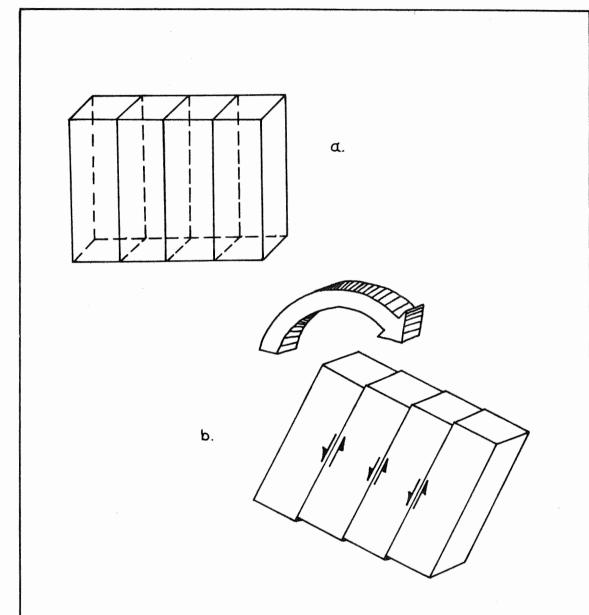


Figure 31. Possible mechanism for dip-slip motions in the Turners Falls area. a) Block diagram showing several fractures. b) Dip-slip motions are created on those fractures by external rotation of the block.

SUMMARY, CONCLUSIONS AND OBSERVATIONS

Summary

A complex history of brittle deformation has acted to produce the observed pattern within the Montague Basin. Basic components of the brittle structure as defined by this study are as follows:

1. Jointing

- a) Joint sets oriented N65E and N70-85W are strongly represented at many outcrops within and surrounding the Montague Basin (Figure 10).
- b) A well-developed N30E set of joints is
 localized in the Turners Falls area (Figure
 12). This set commonly has an orthogonal
 partner which may occur separately in other
 areas. Joints in this part of the Montague
 Basin are systematically tilted with bedding.
 Tilting of joint sets in other parts of the
 basin is non-systematic (Figures 9 and 12).
- c) Some of the jointing in crystalline rocks is similar to jointing in sedimentary rocks (Figures 12 and 13). On a small scale, jointing in the crystalline rocks is more complex than in the sedimentary rocks of the study area (Figure 13). Large joints in the crystalline rocks show a clearer pattern than small joints (Appendix II).

2. Faulting

- a) Fault set orientations are very different from joint set orientations with the exception of the N30E set of joints and the N50E set of faults in the Turners Falls area.
- b) Strike-slip faults with small displacements are common throughout the basin. In some areas, two distinct sets of faults are present. One set varies in strike from N30W to N20W and shows only right-lateral motion, while the other, varying in strike from N30E to N50E, shows both right- and left-lateral motion. They are believed to bear a conjugate relationship to each other.
- c) Dip-slip faults with small displacements are common only in the Turners Falls area. These parallel the northeast-striking set of strikeslip faults.
- d) Strike-slip faults and their σ_2 orientations are perpendicular to bedding. This suggests formation at a time when strata were nearly horizontal.
- e) Orientations of fault sets in two geologically different areas of the Montague Basin, Turners Falls, and Cheapside vary by approximately 20° in strike. Complex rotations to bring bedding

to horizontal do not bring the orientations of these sets into coincidence. Assuming that the two strike-slip sets are conjugate, one of two possibilities can account for this difference in orientation.

- 1) Clockwise rotation of 20⁰ about a vertical axis of the entire Turners Falls area with respect to the Cheapside area. This does not seem geologically probable.
- 2) Curving stress trajectories within the Montague Basin during strikeslip faulting.
- f) At least 14 drape folds associated with normal faults are present in the Turners Falls area.

 They all strike northeast and indicate motion down on the northwest. Cleavage has developed in isolated parts of these folds and they are present 150 meters above the top of the Deerfield Diabase (Figure 26).

Postulated Geological History

- The basin subsided, followed by deposition of the Sugarloaf
 Arkose and extrusion of the Deerfield Diabase.
- 2. Sometime after diabase extrusion, and at least after some of the Turners Falls Sandstone deposition, the basin was

cut by northeast-striking left-lateral faults and northwest-striking right-lateral faults. Both sets varied in orientation throughout the basin. The northeast set experienced right-lateral motion at some unknown later time.

- 3. Basin subsidence continued, with the maximum subsidence occurring near Turners Falls, Massachusetts, where the greatest preserved thickness of Turners Falls Sandstone is present. Gravity sliding from the east may have occurred into this area of maximum subsidence to produce "soft-sediment" folds and other related sedimentary structures. Some joints may have formed at this time, as many joints seem to be tilted with the bedding.
- 4. Tilting of the northern protion of the basin about a northeast-trending axis imposed normal motions on northeast-striking strike-slip faults. Drape folds developed at this time, as did the local N30E set of joints and the isolated areas of cleavage associated with the drape folds. This tilting may have been related to basin subsidence which produced the fault scarp along the eastern border fault as spoken of by Wessel (1969) and Emerson (1898).
- Some joints seem to have formed after all subsidence and tilting as they are rigidly vertical in dipping strata.

Suggestions for Future Study

Future work in key areas which can add to the knowledge of the brittle history of the Connecticut Valley might be:

- A detailed study of fault orientations and motions in the southern Montague Basin. The patterns in this area might support or reject the hypotheses of this study.
- 2. Detailed fault and joint studies in the Brattleboro, Vermont, area north of the Montague Basin. If many of the small faults in the Montague Basin are due to stresses isolated in the cover rocks, as this study suggests, then studies north of the basin where no cover rocks exist will have more significance for the crustal structure and brittle history of the region than this study.
- 3. A detailed fracture study of the Amherst Inlier. Although exposure of these rocks is poor, fracture patterns in this area may help to reveal the tectonic significance of this block of basement rock, which is surrounded by sedimentary fill.

REFERENCES CITED

- Ahmad, Farrukh, 1975, Geological interpretation of gravity and aeromagnetic surveys in the Bronson Hill Anticlinorium, Southwestern New Hampshire: Ph.D. Thesis, University of Massachusetts, 170 p.
- Anderson, E. M., 1951, The dynamics of faulting: London, Oliver & Boyd, 206 p.
- Bain, G. W., 1932, The northern area of the Connecticut Valley Triassic: Am. Jour. Sci., v. 23, p. 57-77.
- ______, 1957, Triassic age rift structures in Eastern North America: Trans. N. Y. Acad. Sci., v. 19, p. 489-502.
- deBoer, J., 1968, Paleomagnetic differentiation and correlation of the Late Triassic volcanic rocks in the Central Appalachians (with special reference to the Connecticut Valley): Geol. Soc. Am. Bull., v. 79, p. 606-626.
- Donath, F. A., 1962, Analysis of basin-range structure South-Central Oregon: Geol. Soc. Am. Bull., v. 73, p. 1-16.
- Emerson, B. K., 1898, Geology of Old Hampshire County, Massachusetts; comprising Franklin, Hampden, and Hampshire Counties: U. S. Geol. Survey Mon. 29, 790 p.
- ______, 1917, Geology of Massachusetts and Rhode Island: U. S. Geol. Survey Bull., 597, 289 p.
- Hafner, J., 1951, Stress distribution and faulting: Geol. Soc. Am. Bull., v. 62, p. 373-398.
- Handin, J. and Hager, R. V., 1957, Experimental deformation of sedimentary rocks under confining pressure: Bull. Am. Assoc. Petrol. Geol., v. 41, p. 1-23.
- Keeler, J. and Brainard, C., 1940, Faulted phyllite east of Greenfield, Massachusetts: Am. Jour. Sci., v. 238, p. 354-365.
- Laird, S., 1974, Geology of the Pelham Dome near Montague, west-central Massachusetts: Univ. of Massachusetts, Dept. of Geology, Contr. No. 14, 84 p.

- May, P. R., 1971, Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in context of the pre-drift position of the continents: Geol. Soc. Am. Bull., v. 82, p. 1285-1292.
- Nickelsen, R., and Hough, V., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geol. Soc. Am. Bull., v. 78, p. 609-630.
- Northeast Utilities Service Co., 1974, Montague Nuclear Power Station, preliminary safety analysis report: Docket No. 50-496 and 497.
- , 1975, Montague Nuclear Power Station, preliminary safety analysis report, Supplement 6, Docket No. 50-496 and 497.
- Onasch, C., 1973, Analysis of the minor structural features in the north-central portion of the Pelham Dome: Univ. of Massachusetts, Dept. of Geology, Contr. No. 12, 87 p.
- Pferd, J., 1975, A computer based system for the collection of detailed structural data from metamorphic terrains (Abs.): abstracts with programs, northeast section, 10th Annual Meeting of Geol. Soc. Am., p. 106.
- Piepul, R., 1975, An analysis of jointing and faulting at the southern end of the eastern border fault, Connecticut: M.S. Thesis, Univ. of Massachusetts, 109 p.
- Price, N. J., 1966, Fault and joint development in brittle and semi-brittle rock: Oxford, Pergammon Press, 176 p.
- ______, 1974, The development of stress systems and fracture patterns in undeformed sedimentary rocks: <u>in</u> Advances in rock mechanics, v. 1, part A, Washington, D. C., National Academy of Sciences, p. 487-496.
- Reynolds, D., and Leavitt, D., 1927, A scree of Triassic age: Am. Jour. Sci., v. 513, p. 167-171.
- Robinson, P., 1967, Gneiss domes and recumbent folds of the Orange area, west-central Massachusetts: Guidebook for fieldtrips in the Connecticut Valley, N.E.I.G.C. 59th Annual Meeting, p. 17-47.

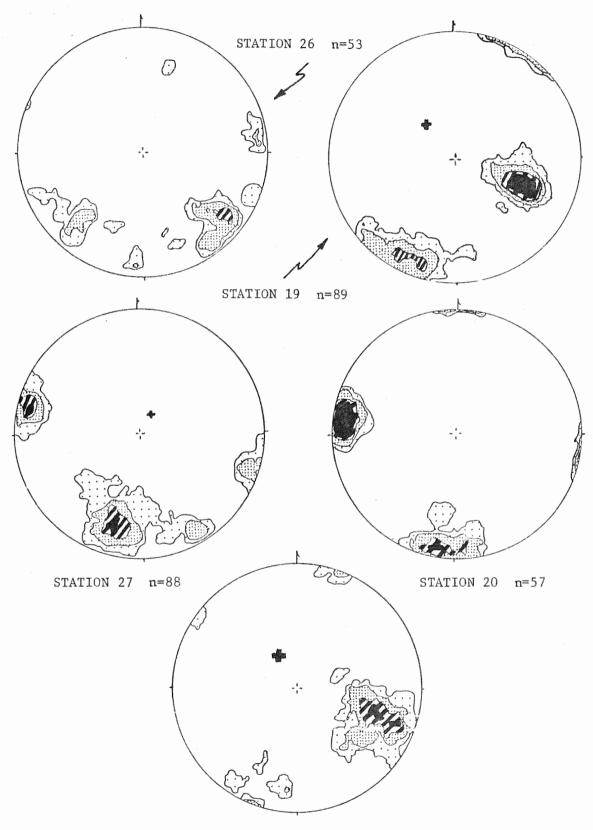
- Sanders, J., 1960, Structural history of the Connecticut Valley belt and its regional implications: N.Y. Acad. Sci. Trans., v. 23, p. 119-132.
- ______, 1963, Late Triassic tectonic history of Northeastern United States: Am. Jour. Sci., v. 261, p. 501-524.
- Wessel, J., 1969, Sedimentary history of upper Triassic alluvial fan complexes in north-central Massachusetts: Univ. of Massachusetts, Dept. of Geology, Contr. No. 2, 157 p.
- Wheeler, G., 1937, The west wall of the New England Triassic lowland: Connecticut State Geol. Nat. History Survey Bull. 58, p. 73.
- _____, 1939, Triassic fault line defections and associated warpings: Jour. Geol., v. 47, p. 337-370.
- Willard, M. E., 1951, Bedrock geology of the Mt. Toby Quadrangle, Massaccusetts: U. S. Geol. Survey Geol. Quad. Map GQ-8.
- ______, 1952, Bedrock geology of the Greenfield Quadrangle, Massachusetts: U. S. Geol. Survey Geol. Quad. Map GQ-20.
- Wise, D. U., 1964, Microjointing in basement, Middle Rocky Mountains of Montana and Wyoming: Geol. Soc. Am. Bull., v. 75, p. 287-306.
- _____, 1965, Rotation axis method for detecting conjugate glide planes in calcite petrofabric: Am. Jour. Sci., v. 263, p. 289-301.
- Wise, D. U., Hozik, M. J., Goldstein, A. G., and Piepul, R. G., 1975, Minor fault motions in relation to Mesozoic tectonics of Southern New England: Trans., Am. Geoph. Un., v. 56, p. 451.

APPENDIX I

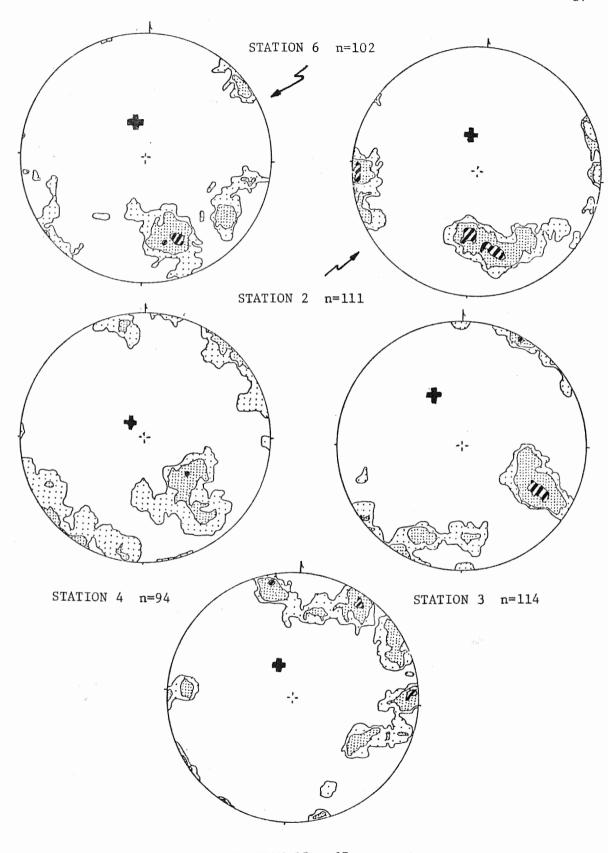
CONTOURED EQUAL-AREA PLOTS OF INDIVIDUAL JOINT SAMPLING LOCALITIES FROM SUBAREAS IN THE MONTAGUE BASIN

Contours are always 2%, 4%, 8%, and 12% per 1% area.

APPENDIX IA - Individual joint stations from the Turners Falls Area.

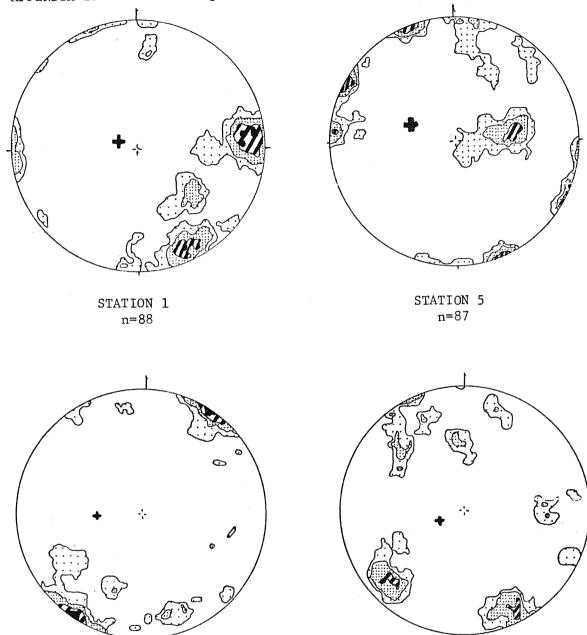


STATION 17 n=103



STATION 15 n=67

APPENDIX IB - Individual joint stations from the Cheapside Area.

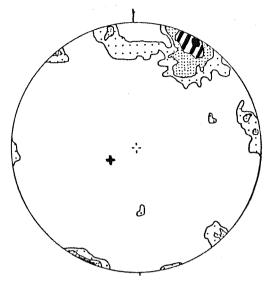


STATION 21

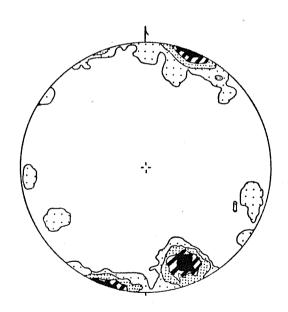
n=118

STATION 22

n=71



STATION 23 n=107

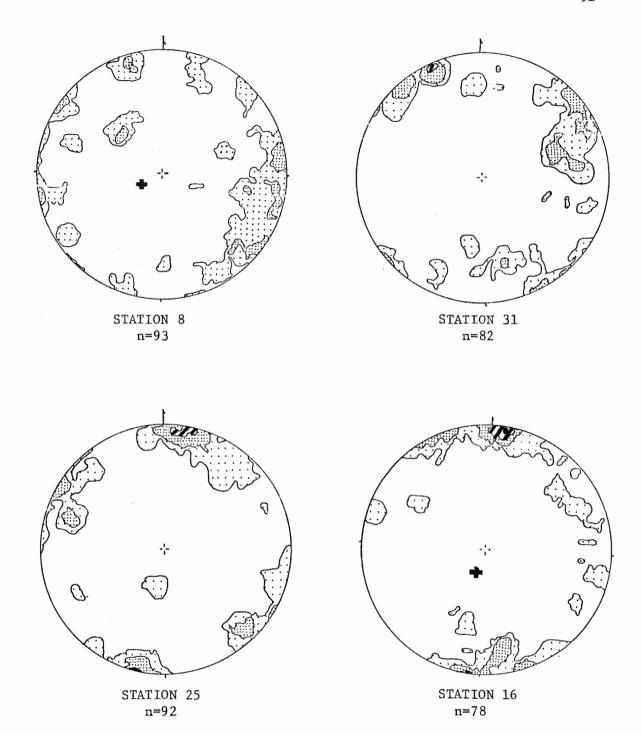


STATION 24 n=98

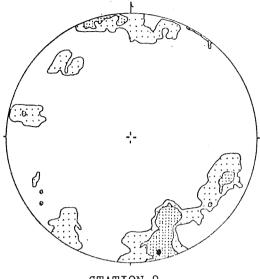
APPENDIX IC - Individual joint stations from the Mt. Toby/Mt. Sugarloaf Area. STATION 18 n=78 STATION 7 n=100

STATION 30 n=94

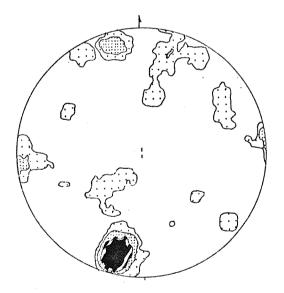
STATION 14 n=110



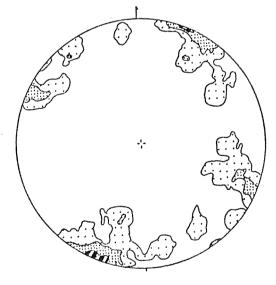
APPENDIX ID - Individual joint stations from the Eastern Basement Area.



STATION 9 n=134

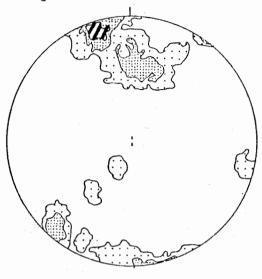


STATION 11 n=91

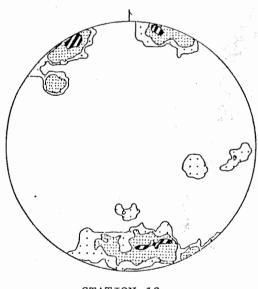


STATION 32 n=89

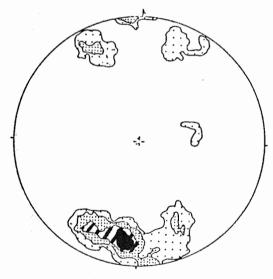
APPENDIX IE - Individual joint stations from the Western Basement Area.



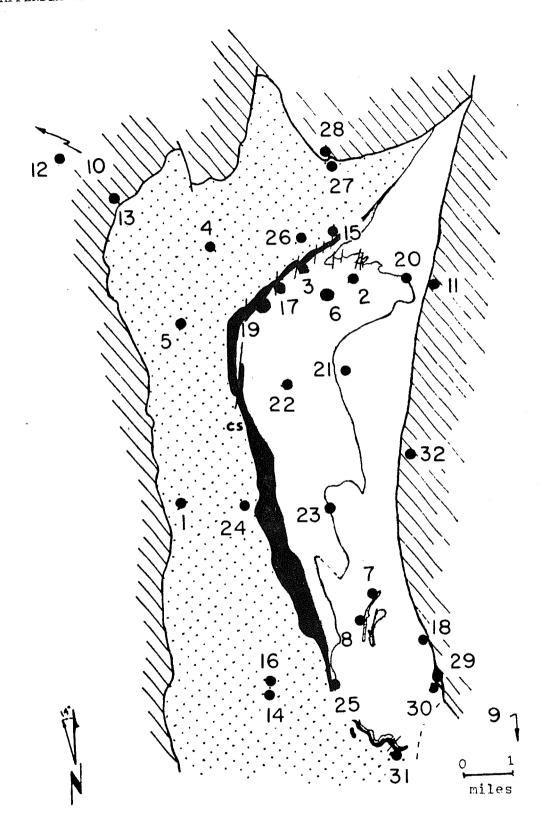
STATION 10 n=87



STATION 12 n=72



STATION 13 n=75



Appendix IG -Fracture Station Location

Station No.	Description of Location
1	Roadcut in Sugarloaf Arkose 1.6 km north of Deerfield River on Rt. 91.
2	Roadcut 4 km west of French King Bridge on Rt. 2.
3	Natural exposures directly below the Dam at Turners Falls, Massachusetts.
4	Roadcut on Rt. 91 2 km north of intersection with Rt. 2.
5,	Roadcut on Rt. 91 2.5 km south of intersection with Rt. 2.
, 6 , , , , , , , , , , , , , , , , , , ,	Natural exposures on east side of Barton's Cove, on the Connecticut River.
7 ************************************	Natural exposure of the contact of the Turners Falls sandstone and the Mt. Toby conglomerate on the east side of Rt. 47 approximately 6 km north of the town of Sunderland, Massachusetts.
8	Natural exposures 1 km east of the North Sunderland Cemetery on Rt. 47 5 km north of the town of Sunderland, Massachusetts
9	Natural exposures on Valley Rd. in Pelham, Massachusetts, 5 km north from its intersection with Pelham Rd.
10	Natural exposures in the Colrain, Massachusetts, area at the 1300-foot level on the west side of Fairbanks Hill 2 km west of the east branch of the North River in the Colrain, Massachusetts, 7-1/2 minute quadrangle and 2.5 km south of the Massachusetts-Vermont border.

Appendix IG Fracture Station Location (Continued)

Station No.	Description of Location
11	Natural exposures on Meadow Road 1 km north of French King Bridge on the east side of the Connecticut River.
12	Natural exposures in the Colrain, Massachusetts, area at the 1,000-foot level in a topographic saddle on the south side of Copeland Hill in the NE 1/4 of the SE 1/4 of the Colrain, Massachusetts, 7-k/2 minute quadrangle.
13	Natural exposures in the Colrain, Massachusetts, area below the power lines west of Shears Hill, 1.5 km west of River Road in Greenfield, Massachusetts.
14	Natural exposures and roadcuts on the west side of South Sugarloaf Mountain near Sunderland, Massachusetts.
15	Roadcut in Turners Falls sandstone on main road in Gill, Massachusetts, 1.5 km north of its intersection with Rt. 2
16	Natural exposures on the west side of North Sugarloaf Mountain near Sunderland, Massachusetts
17	Natural exposures in the bed of the Connecticut River in Turners Falls, Massachusetts, below the bridge to Mountain Road, south of Canada Hill.
18	Natural exposures of the Mt. Toby conglomerate near Roaring Brook on the east side of the Mt. Toby State Forest.
19	Natural exposures in the bed of the Connecticut River below the power lines near the South End School, Turners Falls, Massachusetts.

Appendix IG Fracture Station Location (Continued)

Station No.	Description of Location
20	Roadcut in the Mt. Toby conglomerate on Rt. 2 1.5 km west of the French King Bridge.
21	Natural exposures on the south side of Wills Hill near Turners Falls, Massachusetts.
22	Roadcut on Greenfield Road 2 km east of its intersection with Main Road in Montague City, Massachusetts.
23	Natural exposures on the northwest side of Taylor Hill, in Montague, Massachusetts.
24	Natural exposures on the west face of the Pocumtuck Range near Pocumtuck Rock in Deerfield, Massachusetts.
25	Natural exposures of the contact of the Turners Falls sandstone and the Mt. Toby conglomerate near the Sunderland Town Park, Sunderland, Massachusetts.
26	Natural exposures along the Fall River 1.5 km north of its confluence with the Connecticut River.
27	Natural exposures south of Doyle Road, near Otter Pond, 0.5 km west of Turners Falls Road southeast of the town of Bernardston, Massachusetts.
28	Natural exposures north of Doyle Road near Station #27.
29	Natural exposures in a stream valley on the east face of Roaring Mountain, in the Mt. Toby State Forest, exactly 0.5 km west of Long Plain Road 3.5 km north of its intersection with Bull Hill Road.

Appendix IG -Fracture Station Location (Continued)

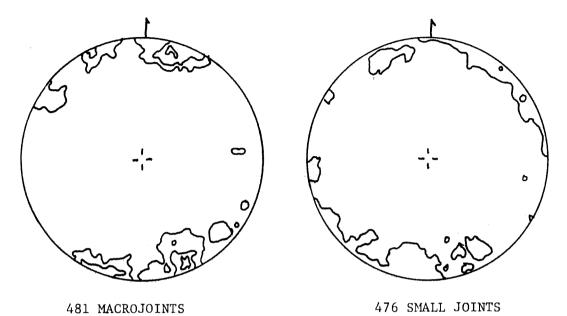
Station No.	Description of Location
30	Natural exposures immediately south of Station 29.
31	Natural exposures immediately north of Bull Hill Road exactly 1 km east of its intersection with Rt. 116 near Sunderland, Massachusetts.
32	Natural exposures on a cliff face 0.5 km south of Dry Hill Road 2 km east of its intersection with Federal Street in Montague, Massachusetts.

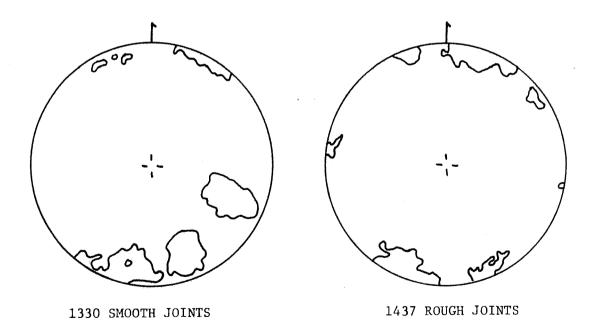
APPENDIX II

SEPARATIONS OF JOINT DATA BY CHARACTER FOR SUBAREAS AND FOR LITHOLOGIC UNITS

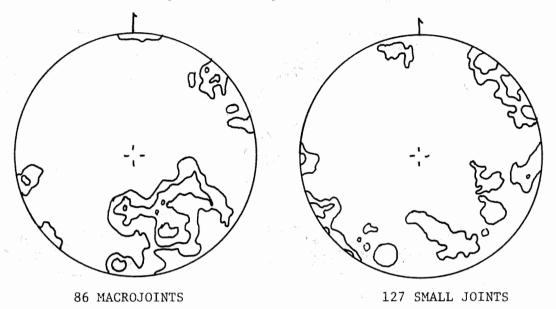
All data are either plotted or contoured on the lower hempsphere of an equal-area net. Contours are always 2%, 4%, 8%, and 12% per 1% area.

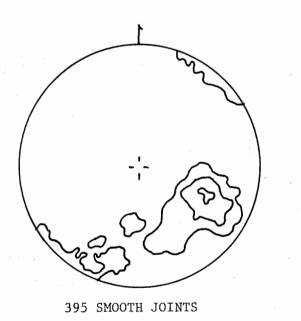
APPENDIX IIA - Separations of all joints measured

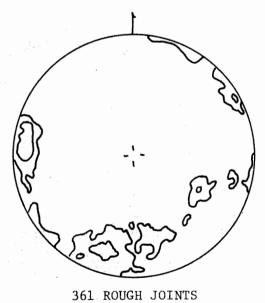




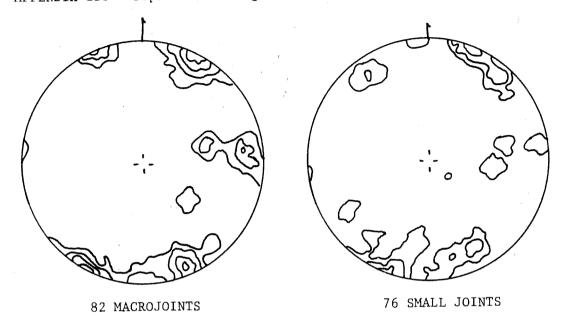
APPENDIX IIB - Separations of joint data from Turners Falls Area

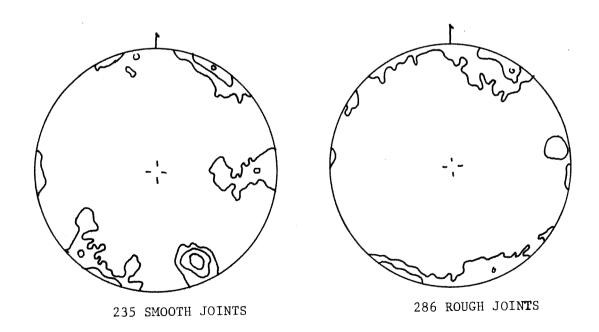






APPENDIX IIC - Separations of joint data from Cheapside Area

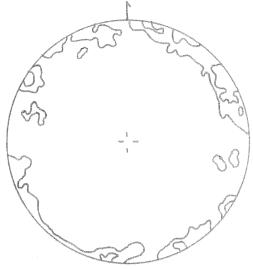




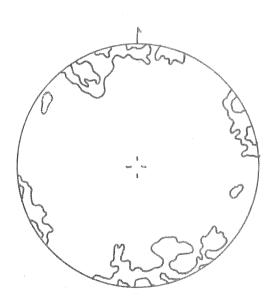
APPENDIX IID - Separations of joint data from Mt. Toby/Mt. Sugarloaf







126 SMALL JOINTS

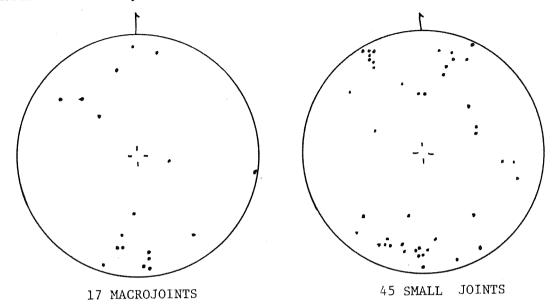


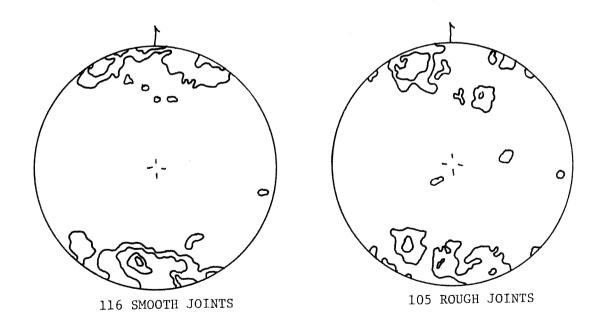
273 SMOOTH JOINTS



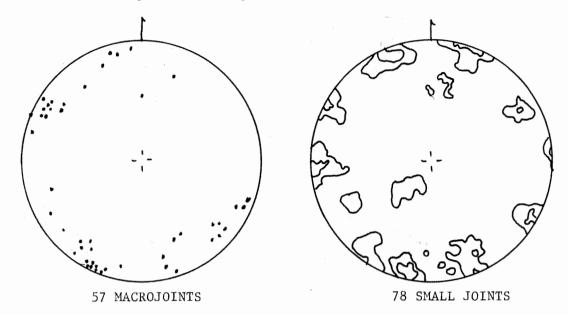
448 ROUGH JOINTS

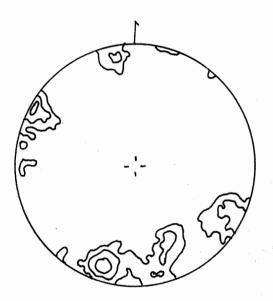
APPENDIX IIE - Separations of joint data from Western Basement Area.



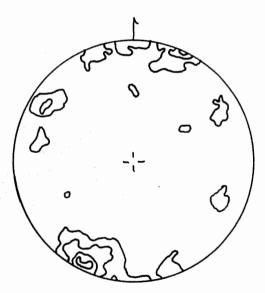


APPENDIX IIF - Separations of joint data from the Eastern Basement Area.



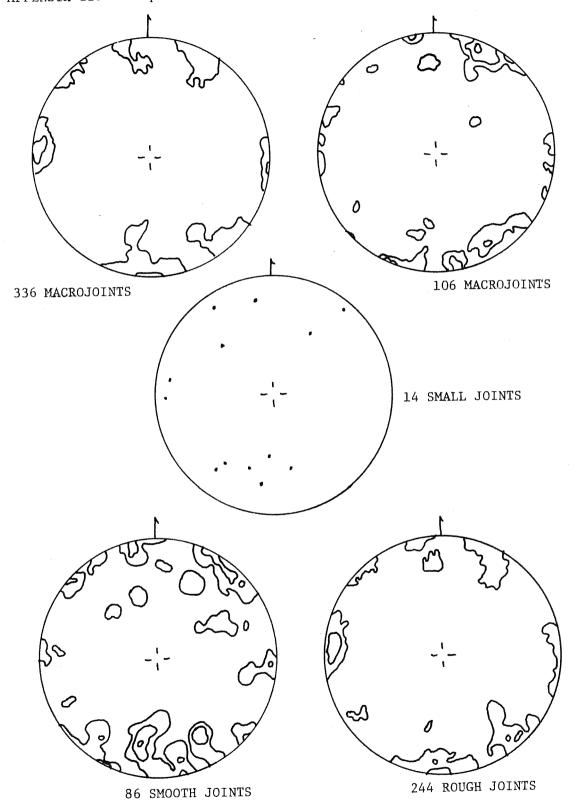




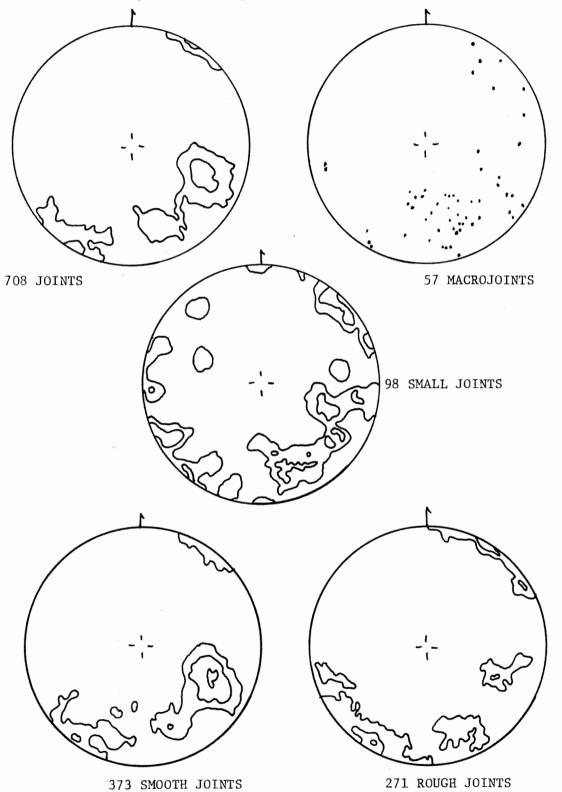


127 ROUGH JOINTS

APPENDIX IIG - Separations of Joints From the Mount Toby Conglomerate



APPENDIX IIH - Separations of joint data from the Turners Falls Sandstone.



APPENDIX IIi - Separations of joint data from the Sugarloaf Arkose.

