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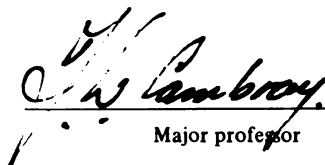
STRUCTURAL ANALYSIS OF FOLIATED PROTEROZOIC
METADIABASE DIKES IN THE MARQUETTE-REPUBLIC
REGION OF NORTHERN MICHIGAN

presented by

Gary A. Myers

has been accepted towards fulfillment
of the requirements for

Masters degree in Geological Sciences


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STRUCTURAL ANALYSIS OF FOLIATED PROTEROZOIC
METADIABASE DIKES IN THE MARQUETTE-REPUBLIC REGION
OF NORTHERN MICHIGAN

By

Gary A. Myers

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geological Sciences

1984

ABSTRACT

STRUCTURAL ANALYSIS OF FOLIATED PROTEROZOIC METADIABASE DIKES IN THE MARQUETTE-REPUBLIC REGION OF NORTHERN MICHIGAN

By

Gary A. Myers

The geology of the Marquette-Republic region of Northern Michigan consists primarily of a highly deformed Proterozoic sedimentary cover (Marquette Range Supergroup) overlying a relatively undeformed granite gneiss basement. The sediments are, in large part, confined to steep sided troughs within the basement. The occurrence of a highly deformed cover overlying an apparently undeformed basement is found in many areas around the world and in many cases the relationship between the two rock units during deformation is difficult to determine.

Sheared Proterozoic metadiabase dikes within the Archean basement are thought to be evidence for basement translation. Assuming simple shear deformation, the dikes were used to determine paleo stress directions. A bulk strain model of deformation was also considered, but rejected.

The study indicates σ_1 was approximately normal to the trough margin regardless of trough orientation and that shear strain was of a maximum close to 45° to the σ_1 direction.

ACKNOWLEDGEMENTS

I am deeply grateful to Dr. Bill Cambray, chairman of my thesis committee, without whose initiative and guidance this work would never have been completed. Thanks also to Dr. Kazuya Fujita and Dr. Tom Vogel for their critical review and helpful discussions during the preparation of the manuscript. Dr. John Wilband's help with the computer generated calculations and plots, which saved my eyesight plus a lot of time, is greatly appreciated. Photo reductions were supplied by the drafting department of the Superior Oil Company. The field work was funded through Geological Society of America Grant #303982 and is gratefully acknowledged here.

Thanks so much to my fellow students for making my stay at MSU so enjoyable. Special thanks to Newbs, Rudi, Mongo, Ben, Mary, Bruce, Jim, and many others for their helpful suggestions and friendship.

My deepest thanks go to my parents and my entire family for their encouragement throughout my entire academic career, and to Jane, my wife, for her undying support and patience during many a long night at the Nat. Sci. building.

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INTRODUCTION

The occurrence of a highly deformed sedimentary cover overlying a relatively undeformed basement is found in a number of areas around the world (Chadwick and Nutnam, 1979; Chadwick et al., 1981; James et al., 1961; Thon, 1978). However, the relationship between the overlying sedimentary sequence and the basement during deformation is not easily determined. These shear zones appear to have been zones of weakness during deformation. Since many basement complexes are riddled with thin igneous intrusions (e.g., potential zones of weakness), it is not surprising to find that many of these intrusions, particularly dikes, show evidence of having undergone ductile shear. The presence of large scale thrusts between the cover and basement suggests a decollement type relationship in some areas, but in other areas where evidence of such thrusting is absent an alternative explanation is needed.

A common feature of many of these cover-basement terranes is the presence of discrete ductile shear zones within the underlying basement. The presence of an oblique internal foliation within dikes has been interpreted to be the result of layer-parallel shear along the dike margin (Berger, 1971; Blyth, 1949; Brindley, 1972; Davidson and Park, 1978; Miller, 1945; Talbot, 1982). The presence of such foliated dikes within a massive basement terrane indicates that deformation has taken place within the basement, albeit along discrete zones. In response to a stress field, these dikes acted as zones of low resistance in an otherwise more competent matrix.

Metadiabase dikes displaying an oblique foliation are found within the Precambrian W basement throughout much of the Marquette-Republic region of Northern Michigan (Figure 1). These localized high strain zones (i.e., sheared

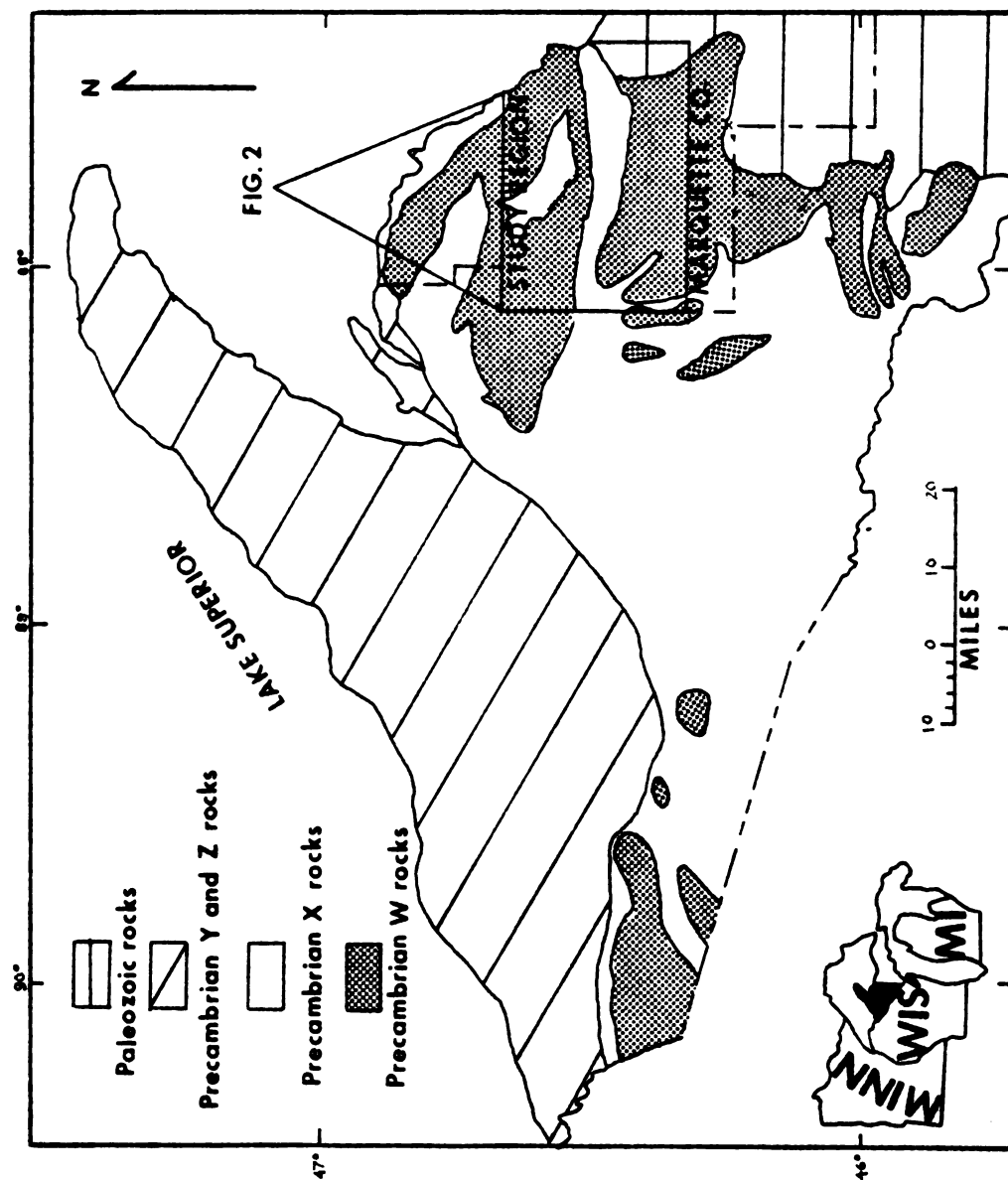
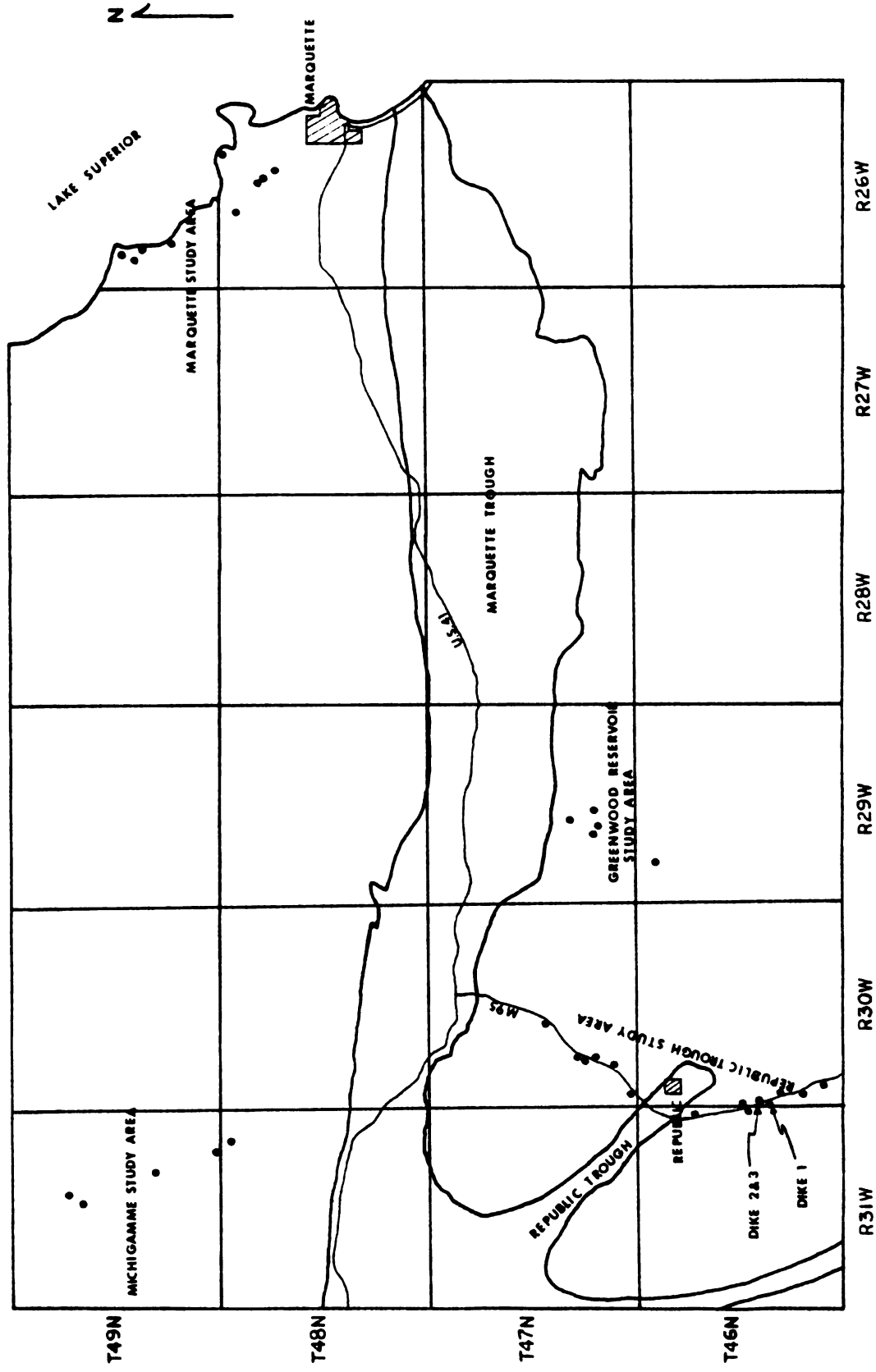


Figure 1. Regional geology map of the western half of Northern Michigan. Modified from Gair and Thaden (1968).



• = Metadiabase dike outcrop locations

Figure 2. Location map of study region defining four local study areas. Dikes 1, 2 and 3 were sampled for detailed crystallographic measurement.

dikes) have been analyzed separately as: 1) Irrotational features which have deformed by simple shear and independent of the immediately surrounding country rock. This model has afforded the determination of the stress pattern during deformation. 2) Rotational features which have deformed with the country rock due to a regional bulk strain. Considering this model, the entire basement (dikes and the surrounding granite gneiss) would have been subjected to a bulk flattening. The structural data from all dikes were separated into four study areas, all within the granite gneiss basement: 1) Republic Trough, 2) Greenwood Reservoir, 3) Michigamme, and 4) Marquette (Figure 2). A stress pattern was derived for each of the four areas and compared to the strain patterns from the same areas. In the past, a north-south direction of compression has generally been given for the Penokean Orogeny. It is hoped that a more quantitative answer can be found to the question of the compressive stress direction, and/or its local variation, at that time.

The overlying sediments (Marquette Range Supergroup) in the Marquette-Republic region are primarily confined to steep sided basement troughs. Cambray (1978) has suggested that the deformation of the overlying sediments has been controlled by the closure of trough margins during deformation. In this case, the basement must have been involved in the deformation and movement may have taken the form of slip along dike walls. Study of sheared dikes surrounding the Marquette and Republic troughs (Figure 2) should facilitate a determination on what affect the closing of these troughs may have had on the adjacent basement during the Penokean Orogeny.

Study of these dikes has been undertaken with the following objectives in mind: 1) to derive stress and/or strain patterns in four separate study areas, each having different geometric relationships to the basement trough margins, 2) to determine whether the sheared dikes are the result of a regional bulk strain

or represent shear in response to a local stress pattern dependent upon heterogeneities within the basement (i.e., basement troughs), 3) to determine the finite strain pattern variation across the foliated metadiabase dikes, 4) to determine the relative finite shear strain variation in foliated dikes of different widths and orientations, and 5) to test the concept of basement control on the deformation of the overlying sediments.

REGIONAL GEOLOGY

The Marquette-Republic region has been involved in two Precambrian orogenic episodes: 1) The Algoman Orogeny approximately 2.7 Ga. (Sims et al., 1980) which resulted in diapiric rise of granitic plutons and metamorphism and remobilization of the Archean basement, and 2) The Penokean Orogeny approximately 1.85-1.90 Ga. (Sims et al., 1980) which caused intense deformation and metamorphism of sediments deposited directly on continental crust (Cannon, 1973). Metamorphism grades from lower greenschist facies to amphibolite (James, 1958).

This study is primarily concerned with the effect of the Penokean Orogeny on the Archean basement. Morey and Sims (1976) and Sims et al. (1980) have noted a "division" in the basement into a greenstone terrane (2.60-2.75 Ga.) to the north of the Marquette Trough and gneissic terrane (approximately 3.0 Ga.) to the south. Directly overlying this basement complex are the Lower Proterozoic (Precambrian X¹) metasedimentary rocks of the Marquette Range Supergroup (Cannon, 1973). This sequence was previously termed Huronian and more recently the Animikie series (James, 1958). The entire supergroup is comprised of a pile of sediments and volcanics unconformably deposited over the Precambrian basement. The majority of these sediments are concentrated in steep sided basement troughs. Cambray (1978) envisages the development of such troughs as a response to insipient rifting. Evidence for this is a general

¹ All Precambrian dates will be referred to the W, X, Y, Z time division used by the U.S.G.S. For comparison of various terms and dates to this system, see Cohee and Wright (1976).

sedimentary sequence which suggests a period of subsidence, indicated by an early shallow water depositional environment, followed by subsiding, restricted basins and finally regional subsidence producing extensive mass flow sedimentation. Intrusion of diabase dikes and sills also occurred at this time in response to an extensional stress regime.

Most of the early work and preliminary mapping was done by Van Hise and Bayley (1897) and Van Hise and Leith (1911). Until the early 1970's, most of the papers written were concerned with the origin and accumulation of the Precambrian X sediments. This was mainly due to the large, economically productive iron ore deposits present in this sequence. Recently, many workers have looked at the underlying Archean basement for clues to help explain the mode of deformation during the Penokean and how it may have controlled both deposition and deformation of the sediments. In light of the plate tectonic theory, Van Schmus (1976) and Cambray (1978) have proposed a suture zone of collisional nature producing compressional forces, while others have adopted a purely basement controlled model for the deformation (Cannon, 1973; Sims, 1976; Sims et al., 1980).

The above authors have distinctly different views on what caused the deformation during the Penokean Orogeny. James (1954) notes that the close or restricted environment, probably required for iron formation deposition, suggests the evolution of offshore swells or buckles within the basement that subsequently developed into volcanic island arcs. He suggests that the deformation of the Precambrian X sediments was controlled by basement faulting during compression.

Cannon (1973) suggests that the wide divergence of first order structural trends (basement troughs) in the area can be explained by vertical movement along basement block faults, thus alleviating the need for a horizontal

compression. He also notes that mafic sills which intrude the Precambrian X sediments are commonly folded, whereas dikes of comparable composition and age cutting the Precambrian W basement show no evidence of folding. He concluded that gravity sliding, responsible for many of the second order structures (i.e., folds), occurred first. This was followed by an episode of basement block faulting, whereby the Precambrian X sediments were passively draped over the Archean basement.

Sims (1976) proposed that reactivation of the boundary between the two basement terranes (greenstone and gneissic) was the cause of deformation in an intracratonic event, precluding any plate tectonic model. He points to differential thermal contraction and expansion caused by crustal and/or mantle processes as a driving mechanism for the reactivation (Sims et al., 1980).

Van Schmus (1976) proposed a plate tectonic setting where a north dipping subduction zone lies to the south of presently exposed Precambrian rocks. Uplift of the continental crust created a submarine barrier to the south and could explain the depositional transition of miogeoclinal sediments, like orthoquartzites and carbonates, to the presumably more restricted depositional environment of sedimentary iron formation. However, the discovery of Archean crust in central Wisconsin (Van Schmus and Anderson, 1977) suggests that a subduction zone would have been in a different locality, with a downgoing slab dipping to the south, but does not dismiss a plate tectonic model entirely.

Cambray (1977, 1978) adopts a plate tectonic model, but with further explanation as to a deformation mechanism within the basement and its relationship to the overlying sediments. He agrees with Van Schmus (1976) in the development of a subduction zone following deposition, thus creating a compressional stress state on the sediments and underlying Precambrian W basement. However, Cambray (1978) proposes that the suture zone lies near the

Michigan-Wisconsin border. The Wisconsin granites and rhyolites, in this model, represent the cordilleran type margin of a plate which is overriding a plate to the north along a south dipping subduction zone. He states that although the dikes which have intruded the basement have not been folded, they are indeed deformed. He points to originally diabasic textures which have been destroyed, and in some cases developed into a foliation, as evidence for this deformation. The folds in the overlying Marquette Range Supergroup (MRS)² are apparently the result of basement movement progressively closing the troughs.

²Marquette Range Supergroup - hereafter will be abbreviated to MRS.

METADIABASE DIKES

Field Description

Forty-nine metadiabase dikes were used for detailed structural and petrographic analysis (Figure 2). Roadcuts, ridges, and areas adjacent to bodies of water offered the best exposure of both the dikes and the surrounding granite gneiss. However, in some outcrops, the dikes and basement were covered with thick, wet moss, making structural measurements and sampling extremely difficult.

The dikes are typically straight sided, with few irregular jogs and very little evidence of buckling or folding. As a group, they are steeply dipping at angles ranging from 70° to vertical and have widely varying strikes. In outcrop, their color ranges from dark black with randomly oriented plagioclase laths, to a more greenish, less massive variety containing elongate amphibole crystals. Texturally, they range from fine grained, poorly foliated, to a coarser grained, highly foliated variety in some cases resembling chlorite schist zones. The nature of the texture appears to be related to two factors: 1) the strike of the dike, and 2) the width.

Nearly all of the dikes possess an oblique, sinusoidal, internal foliation. The internal foliation near the dike margins makes a small angle to the dike wall, progressively becoming larger toward the dike interior (Figure 3). Based solely on field evidence, it could be concluded that the foliation has developed due to slip along the dike walls in response to an applied stress within the basement (Figure 4).

The surrounding basement, consists primarily of a well foliated granite gneiss complex. Cannon (1975) has noted at least three separate structural units

Figure 3. Photograph of a metadiabase dike in the Republic Trough area displaying a sinuous internal foliation.

Figure 4. Schematic diagram of two foliated dikes which have undergone dike wall shear. Note the relationship between dike orientation, applied stress direction, and sense of shear.



FIGURE 3

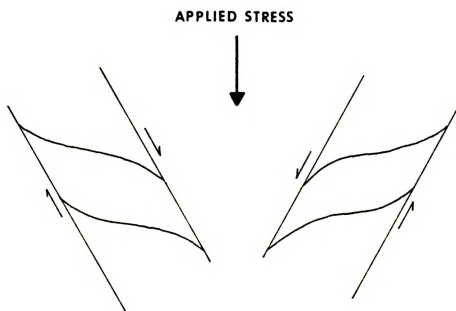


FIGURE 4

defined by slight textural and mineralogical changes, but overall the granite gneiss basement is medium to coarse grained (megacrysts ranging up to 5 centimeters), well foliated and consisting primarily of potassium rich feldspar (microcline and orthoclase), and quartz, and plagioclase with minor amounts of biotite and chlorite. Although it is thought that the granite gneiss basement would be more resistant to shear strain than the metadiabase dikes, textural changes in the basement are evident directly adjacent to the dike wall. There is a gradual change in the strike of the granite gneiss foliation extending from approximately 7 centimeters into the country rock to the dike wall where it nearly parallels the foliation of the dike (Figure 5). There are, however, no large scale deviations of the granite gneiss foliation beyond a few centimeters and otherwise the two opposing foliations are nearly always oblique to each other.

Sample Description

The mineralogy and texture of the metadiabase dikes is widely variable both within individual dikes and throughout the Marquette-Republic region. James (1955) has outlined five regional metamorphic zones representing three different metamorphic facies within the region (greenschist, epidote-amphibolite, and amphibolite). Metamorphic isograds are centered about the southeast closure of the Republic Trough where the metamorphic grade is upper amphibolite. This has been termed the Republic metamorphic node (James, 1955, p. 1457). The Marquette and Michigamme areas appear to represent areas of lower greenschist metamorphism, while the Greenwood Reservoir and Republic Trough areas are of amphibolite grade metamorphism. The Republic Trough area represents the highest grade rocks under study.

The dikes consist of amphibole (30-70%, primarily hornblende), plagioclase (10-45%), quartz (Tr-15%), biotite (Tr-25%), chlorite (Tr-10%), epidote/clinozoisite (Tr-8%) with minor amounts of muscovite, sphene, opaques



Figure 5. Photograph of a metadiabase dike/granite gneiss contact showing a gradual change in the strike of the granite gneiss foliation close to the dike wall. Scale is 2 centimeters in length.

(primarily magnetite), and calcite. Hornblende ranges in size from 0.1-1.0 mm in cross-sections and 0.2-6.0 mm along elongate sections with straight to highly curved or serrated crystal boundaries. Crystal form is generally pseudomorphic after pyroxene with very faint green pleochroism in low metamorphic grade areas (Figure 6) and well developed prismatic crystals showing strong pleochroism from green to bluish green to occasionally faint brown in higher grade areas (Figure 7). Plagioclase ranges in size from 0.1 mm across equant crystals to 1.0 mm along elongate laths. Sericitization of plagioclase is widespread and, in some cases, has completely replaced plagioclase. Muscovite also appears to be an alteration product of plagioclase. Quartz seems to be more abundant in high grade metamorphic areas. It is commonly interstitial between hornblende and plagioclase or poikilitic within large hornblende porphyroblasts, generally equant in shape and approximately 0.1 mm across. Biotite is generally absent (except near dike margins) in the extremely low grade areas of the Marquette and Michigamme study areas, but common as straight sided elongate crystals with serrated ends in higher grade areas. Chlorite is present throughout rocks of lower greenschist grade metamorphism, and is also present in varying amounts in higher grade areas. Epidote and clinozoisite crystals and clinozoisite are common in low grade metamorphic areas, but are also found in minor amounts within dikes of upper amphibolite grade. Crystals are generally 0.4-0.5 mm across and elongate to irregularly shaped in greenschist grade areas, while in higher grade areas, they are generally smaller (0.05-0.2 mm across) and highly irregular.

These observations generally agree with those of James (1955). It is apparent that there is an increase in regional metamorphic grade from the Marquette study area southwest to the center of the Republic Trough study area.

Figure 6. Photomicrograph of a metadiabase dike of low regional metamorphic grade. Yellowish, high relief crystals are epidote.

Figure 7. Photomicrograph of a metadiabase dike of high regional metamorphic grade.

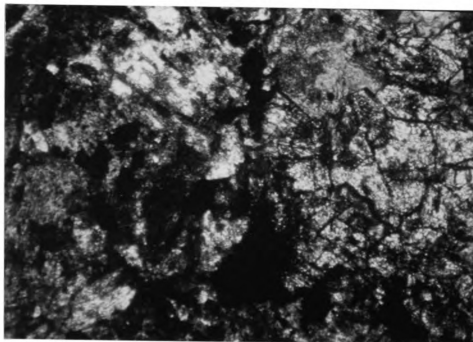


FIGURE 6

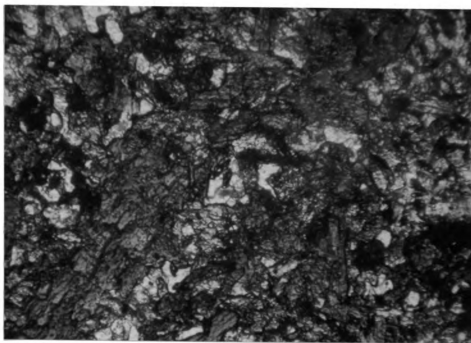


FIGURE 7

However, the presence of James' (1955) circular metamorphic isograds about the Republic Trough cannot be confirmed due to the limited distribution of samples.

The two margins of an obliquely foliated dike can be envisaged as two adjacent shear zones, where two areas of high shear strain (i.e., dike margins) are separated by a low shear strain zone (i.e., the dike interiors). The effect of dike wall shear has greatly altered both the texture and mineralogy of the metadiabase near the margins. This shear effect has "overprinted" the mineralogical and textural features attributed to the regional metamorphism.

Crystals tend to be better developed (more euhedral) near dike margins. Taking hornblende as an example, there is a gradual change from irregular mat or elongate crystals with curved or serrated boundaries in dike interiors (Figure 8) to more euhedral crystals displaying generally straight boundaries near the dike margins (Figure 9). Hornblende crystals within dike interiors commonly show evidence of rotation indicated by bent or curved cleavage traces and crystal boundaries (Figure 10). This may indicate that higher shear strains, near the margins resulted in recrystallization, while less strained interiors deformed by crystal rotation. It is also clear that preferred orientation (based on inspection) of all minerals, especially hornblende, is best developed near dike margins and commonly present in interiors, but to a lesser degree. The presence of fine grained, well developed crystals within the interior of some dikes suggests that both recrystallization and crystal rotation may have been responsible for the preferred orientation.

Several sheared dikes containing well developed marginal foliation display a gradual increase in percent biotite toward the dike margin. This is occasionally accompanied by the concentration of chlorite directly adjacent to the sheared dike margins. Many of these observations were from dikes found in high grade (amphibolite facies) regional metamorphic areas, generally thought to

Figure 8. Photomicrograph of the interior of a metadiabase dike. Preferred orientation is faint and crystal shape is subhedral to anhedral.

Figure 9. Photomicrograph of the margin of a metadiabase dike. Preferred orientation is well developed and crystal shape is euhedral to subhedral. Note: Figures 8 and 9 are from the same dike.

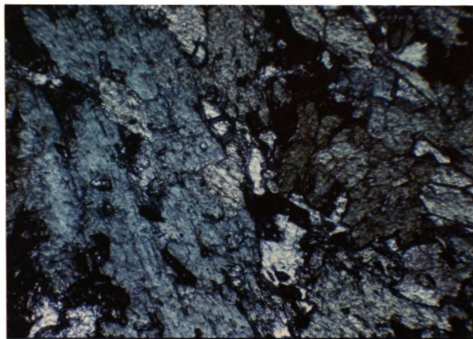


FIGURE 8

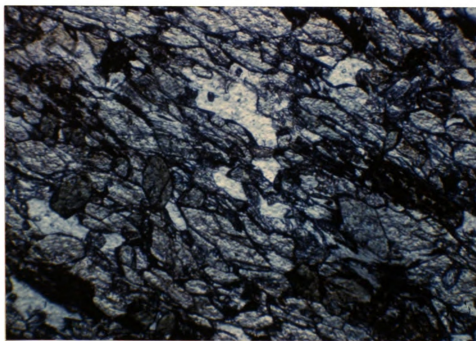


FIGURE 9

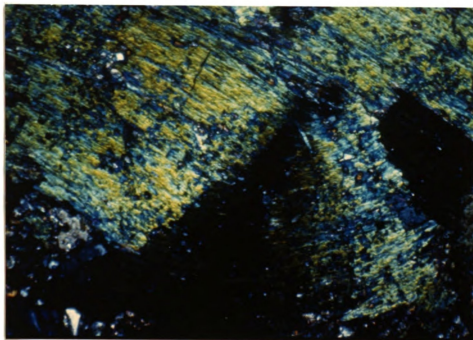


Figure 10. Hornblende crystal from a dike interior displaying curved cleavage traces and crystal boundaries.

be devoid of chlorite. It is also evident that much of this chlorite has formed at the expense of hornblende. Wiseman (1934) concluded from similar observations within the Southwest Highland Epidiorites, that such mineralogic changes are the result of shear along the margins of the igneous body.

Considering a sheared dike as two discrete shear zones and assuming deformation by simple shear, the methods of Ramsay and Graham (1970) can be applied to determine the relative shear strain variation from the dike margins to the interior. This is based on the following simple equation:

$$2\theta' = 2\gamma$$

where γ is the shear strain and θ' is the angle between the maximum elongation direction (or XY plane of strain) and the shear direction (or the walls of the shear zone). In this study, the internal foliation is assumed to parallel the XY plane (Ramsay and Graham, 1970). It is apparent that as θ' decreases, the shear strain increases.

In nearly all cases where internal foliation was measurable throughout a dike, the dihedral angle between the dike wall and the internal foliation was small near each margin and gradually increased toward the interior (Figure 4). This suggests a decrease in the relative shear strain away from the margins and toward the dike interior, and indicates that the mineralogical and textural changes observed are, at least in part, the result of shear strain variation.

FINITE STRAIN PATTERNS FROM PREFERABLY ORIENTED AMPHIBOLES

The finite strain pattern within the foliated metadiabase dikes was derived by measuring the preferred orientation of minerals. This was accomplished by using the universal stage. Hornblende was selected as the mineral to be used in this analysis because it is generally present in high percentages throughout all metadiabase dikes in the Marquette-Republic region. The crystallographic c-axis orientation of hornblende crystals has been determined by measuring the orientation of the two prominent planes of cleavage within each crystal. The intersection of these cleavage planes defines the c-axis of each individual crystal. In other words, it will yield the orientation (plunge and plunge direction) of the long axis of an elongate hornblende crystal. The internal foliation, as seen in the dikes, has been defined as paralleling the XY plane of finite strain, and a lineation produced by the preferred orientation of elongate minerals, such as hornblende, is thought to represent the maximum elongation direction (X) on the XY plane (Ramsay, 1967; Ramsay and Graham, 1970).

Samples from three differently oriented dikes (numbered 1, 2, and 3 on Figures 2 and 11) were chosen from the center of the Republic metamorphic node for petrographic analysis. Dike margins and interiors were sampled so as to note any variation in the finite strain pattern across the dikes. It is clear from Figure 12a through 18g that the measured finite strain pattern of these dikes is generally defined by a near horizontal X and Z finite strain direction and a near vertical Y direction, with a steeply dipping XY plane of strain. However, variations in the trend of the principal planes within individual dikes are obvious and may be the result of variable magnitudes of shear strain (Ramsay and Graham, 1970).

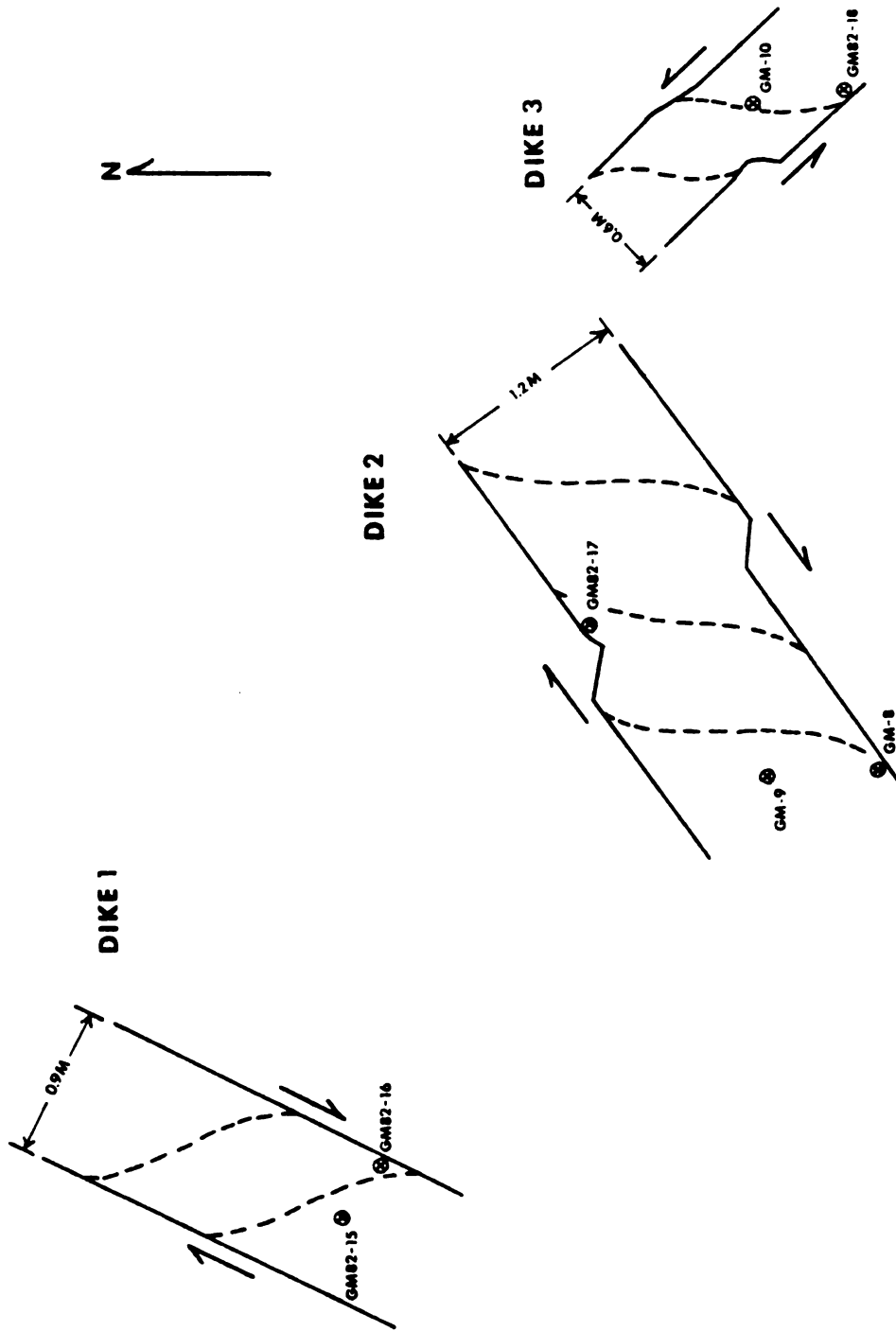


Figure 11. Field sketch of dikes 1, 2, and 3 with the location of individual samples. The internal foliation pattern (dashed lines) and the sense of dike wall shear (arrows) are shown for each dike. The distance between the dikes is relative and not to scale.

Three thin sections from each sample were analyzed. Each thin section was oriented differently with respect to the foliation and lineation: 1) perpendicular to the foliation and the lineation, 2) perpendicular to the foliation and parallel to the lineation, and 3) at an intermediate angle to both the foliation and lineation, and to the other two thin sections. In an effort to arrive at a statistically valid result, the sampling procedure of each thin section involved measuring crystals at regular intervals along parallel, evenly spaced traverses (Turner and Weiss, 1963). The number of crystals measured per sample ranged from 108 to 184. It should be noted that tabular or prismatic crystals have no doubt been preferably measured over poorly developed, irregularly shaped crystals. This has resulted from the inability to measure, or even observe, cleavage planes within irregularly shaped crystals. However, the data are considered to be representative of the preferred orientation within each sample since 1) all of the samples analyzed are of high regional metamorphic grade and contain primarily well formed, prismatic hornblende crystals, and 2) three differently oriented thin sections were analyzed so as to avoid a biased sampling within a single plane.

Figures 12a and 12b are the contoured diagrams of hornblende c-axes from samples GM82-18 and GM-10, respectively. Note the clearly defined concentration near the primitive, particularly in Figure 12, defining a near horizontal X direction of strain. Particularly noticeable is the change in the strike of the XY plane of strain from sample GM82-18 to GM-10. The X direction and XY plane lie closer to the trend of the shear plane (i.e., dike wall) in sample GM82-18, which indicates that shear strain was greater near the margin (Ramsay and Graham, 1970). Figures 12c and 12d are the collective contoured diagrams of hornblende c-axis orientations from samples GM82-16 and GM82-15, respectively. The X direction of finite strain is again found to be near

Figure 12. Contoured stereograms of hornblende C axes measured in samples collected from dikes 1, 2, and 3. Small arrows indicate the strike of the adjacent dike wall. Dashed lines represent the best fit position.

- a) Dike 3, sample GM82-18, contoured at 2, 4, 6, 8, 10, and 12 percent.
- b) Dike 3, sample GM82-10, contoured at 2, 4, and 6 percent.
- c) Dike 1, sample GM82-16, contoured at 2, 4, 6, and 8 percent.
- d) Dike 1, sample GM82-15, contoured at 2, 4, and 6 percent.

Figure 12 (continued). Contoured stereograms of hornblende C axes measured in samples collected from dikes 1, 2, and 3. Small arrows indicate the strike of the adjacent dike wall. Dashed lines represent the best fit position.

- e) Dike 2, sample GM-8, contoured at 2, 4, 6, and 8 percent.
- f) Dike 2, sample GM82-17, contoured at 2, 4, 6, and 8 percent.
- g) Dike 2, sample GM-9, contoured at 2 and 4 percent.

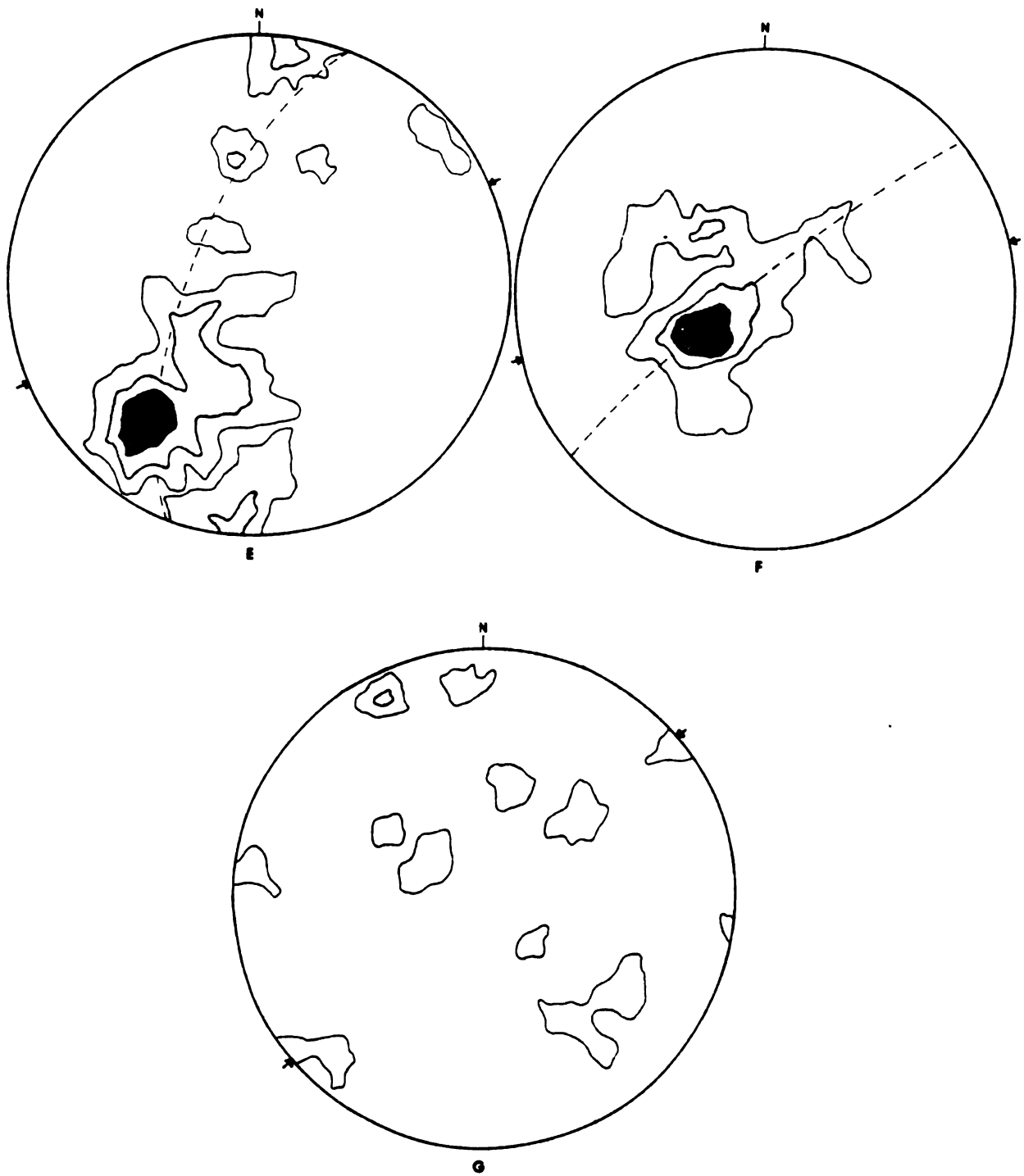


FIGURE 12 (continued)

horizontal and the XY plane in both GM82-16 and GM82-15 is steeply dipping and trends nearly parallel to the plane of shear. Parallelism of the XY plane on the dike margin and in the interior suggests that there was not a great difference in the shear strain magnitude across dike 1. However, closer review of Figures 12c and 12d show a wider scatter of data from sample GM82-15, indicating that the preferred orientation of hornblende was less well developed, possibly due to lower shear strain. Figures 12e, 12f, and 12g are the collective contoured diagrams of hornblende c-axes for samples GM-8, GM82-17, and GM-9, respectively. The finite strain pattern of sample GM-8 (Figure 12e) indicates a steeply dipping XY plane of strain and a shallowly plunging X direction. Contrary to this, the contoured stereoplot of GM82-17 suggests a rather steeply plunging (approximately 70°) X direction. Although sample GM82-17 displays a somewhat anomalous finite strain pattern from previously derived patterns near dike margins, it should be noted that this sample was located near an irregular feature in the dike wall (Figure 12f), and may be the result of a locally steep shear direction. However, this cannot be confirmed by evaluation of the complex foliation near the dike wall irregularity. Sample GM-9 (Figure 12g) is the only sample analyzed which lacks evidence of a well defined preferred orientation. The distribution of hornblende c-axes defines neither a point maxima on the stereoplot (i.e., a lineation) nor an alignment along a single plane (i.e., a foliation). It is evident from the very wide scatter of data represented in Figure 12g that the interior of dike 2 was subjected to a much lower shear strain than the adjacent margins.

The angle between the dike wall and measured XY plane of strain shown in Figures 12a through 12f is equivalent to the angle θ' , used in Ramsay and Graham's (1970) shear strain equation (see page 11 of this study for the full equation). Applying this equation to the data of Figures 12a and 12b (dike 3)

indicates a lower shear strain magnitude within the dike interiors. The measured XY planes shown in Figures 12c and 12d of dike 1 define small angles to the dike wall in both the dike margin and the interior, and suggest that the magnitude of shear strain was only slightly less in the center of the dike.

Ramsay and Graham (1970) have shown that if it is possible to determine the shear strain at several points across a shear zone, the total displacement (i.e., total shear strain) across the zone can be computed by integrating these shear strain values. The following equation can be used:

$$S = \int_0^X \gamma \, dx = \text{Total Shear Strain}$$

where dx is the distance between individual shear strain measurements across the shear zone. A computation of this sort is not attempted on these three dikes due to the lack of sufficient measurements between the dike margins and the interior. However, inspection of the strain patterns represented in Figures 12a and 12b, and Figures 12c and 12d indicate that the total shear strain was probably greater in dike 1 than dike 3.

Although the margins of dike 2 have fairly well defined XY planes of strain, the interior (Figure 12g) displays a random distribution of hornblende c-axes, such that an XY plane cannot be defined. Note that dike 2 is wider than both dikes 1 and 3 (Figure 11) which could account, in part, for the relatively greater differential shear strain between the margins and the interiors. The apparent dichotomy in the degree of preferred orientation observed in the dike margins and the interiors of these dikes, particularly dike 2, also suggests that the margins have undergone a higher degree of shear strain, and that each dike has undergone a different total shear strain, apparently dependent upon its orientation.

METHODOLOGY

Structural data from sheared dikes in the four study areas were analyzed using three separate methods. Two of these were used to derive a stress pattern responsible for the deformation of the basement in each study area (Berger, 1971; Davidson and Park, 1978). A third method has been employed to analyze the role of sheared dikes during a regional bulk strain (Talbot, 1982). The methods for stress analysis assume that the dikes have not undergone gross bodily rotation and have been deformed by simple shear independent of the surrounding country rock. On the otherhand, the method for analysis of a bulk strain assumes that the dikes have deformed with the country rock and features such as buckled or folded dike margins are seen as evidence for dike rotation.

Berger (1971) and Davidson and Park (1978) view the deformation of dikes within a host granite or granite gneiss body as a more or less rigid body reacting to stress solely by slip along a series of planar zones (i.e., dikes). Berger (1971) has applied the methods of stress analysis developed by Carter and Raleigh (1969) for deformation by twin and translation gliding in crystals. In this case, the dikes represent the twin or glide planes and the host country rock represents the crystals. It is assumed that slip will occur along planes oriented such that the critical resolved shear stress is exceeded. Theoretically, this occurs when σ_1 makes an angle of 45° to the slip plane (Carter and Raleigh, 1969; Watterson, 1968). The maximum principal stress axis is derived by measuring 45° from the slip plane, in the plane normal to it and containing the slip direction, while σ_2 lies on the slip plane, normal to the slip direction (Berger, 1971). Carter and Raleigh's (1969) analysis relies on a series of randomly oriented glide or twin planes to derive a statistically valid result. This may be common in petrofabric

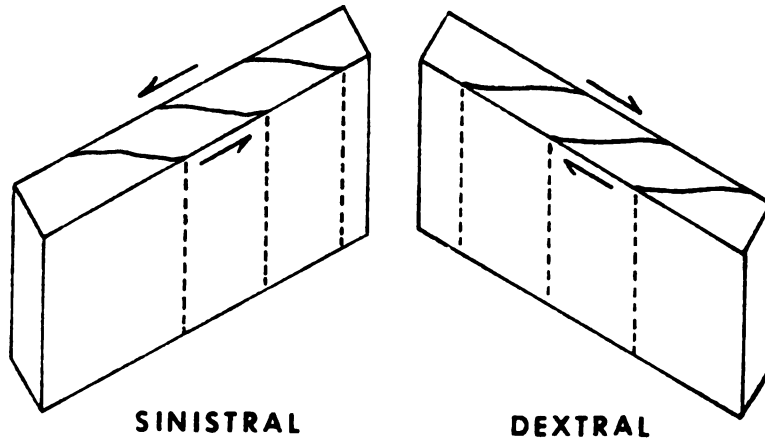
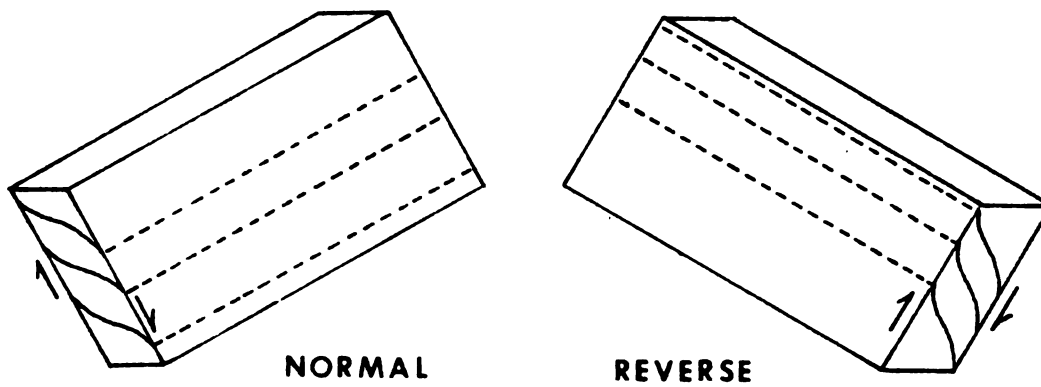
studies but is probably rare when dealing with a suite of dikes which are usually intruded during a period of regional extension, thus inducing a preferred orientation.

Davidson and Park (1978) have introduced a similar method of stress analysis, but independent of dike orientation. A step-by-step procedure of constraining the position of the principal stress axes is used.

Step 1: The first step is the construction of a histogram showing the trend in degrees of the dikes displaying sinistral or dextral sense of horizontal shear versus the number of dikes. By noting the change from dextral to sinistral shear, the strike of the locus of no horizontal shear and the locus of no shear can be approximated.

Step 2: Assuming a biaxial stress system ($\sigma_1 > \sigma_2 = \sigma_3$), a best fit position of σ_1 and the $\sigma_2\sigma_3$ plane is found by plotting poles to sheared dikes on a stereogram which will then define quadrants of dextral and sinistral sense of shear in the horizontal component of shear. These quadrants are separated by the $\sigma_2\sigma_3$ plane and the vertical plane representing the locus of poles to planes of no horizontal shear. The $\sigma_2\sigma_3$ plane is constrained by the data and represents the locus of poles to planes of no shear, while σ_1 lies on the locus of no horizontal shear. To confirm the derived σ_1 position, a stereogram showing poles to dikes differentiated into normal and reverse sense of the vertical component of shear are plotted. The $\sigma_2\sigma_3$ plane (i.e., plane of no shear) separates fields of normal and reverse sense of vertical shear, while the σ_1 position is constrained by lying on the locus of poles to planes of no vertical shear. Note that a near horizontal σ_1 will result in nearly an entire field of potential reverse sense of vertical shear, while a vertical σ_1 would produce only potential normal sense of vertical shear. In all cases, the sense of shear in both the horizontal and vertical planes is determined from the orientation of the oblique foliation with respect to

Figure 13. Three dimensional sketch showing the relationship between the internal foliation and sense of dike wall shear in a) the horizontal component of shear, and b) the vertical component of shear.

A**HORIZONTAL SHEAR****B****VERTICAL SHEAR****FIGURE 13**

the dike walls (Figure 13). Davidson and Park (1978) define the direction of maximum shear stress (i.e., slip direction) in a biaxial stress system as parallel to the effective shear component of σ_1 on the shear plane (Figure 14). In light of a triaxial stress system, to be described below, σ_1 is termed the "predicted shear direction", which is defined by the intersection of the shear plane and the plane containing both σ_1 (as derived above) and the pole to the shear plane.

Step 3: When a triaxial stress system ($\sigma_1 > \sigma_2 > \sigma_3$) is considered, the orientation of the maximum shear stress moves toward the σ_3 component on the shear plane (Figure 14b). This movement is mimicked by the rotation of points X to Y on the $\sigma_2\sigma_3$ plane. These points are found by drawing planes through the pole of the sheared plane, to the predicted and observed shear directions, respectively. The observed shear direction is normal to the line of intersection between the external foliation and the dike wall (Watterson, 1968).

The bulk strain analysis, developed by Talbot (1982), is employed to offer an alternate explanation for the deformation of the metadiabase dikes under study here. In a homogeneously strained body, poles to planes undergoing rotation will move toward the maximum shortening direction (Z) or ZY plane of the strain ellipsoid (Ramsay, 1967). Talbot (1982) views foliated dikes as the planar features undergoing rotation in a homogeneously strained body (i.e., the basement). The paths traced by these poles have been called "structural movement paths" by Flinn (1962). Poles to planar elements within a rock mass that displays completely homogeneous strain (on all scales) can represent only a single point on its own structural movement path (i.e., the end of the structural movement path). However, strain inhomogeneities such as foliation in deformed incompetent dikes can be used to record complete structural movement paths if a relationship between the behavior of the dike margin and the foliation during a bulk strain can be determined (Talbot, 1982).

Figure 14. The effective shear components of σ_1 , σ_2 , and σ_3 on a shear plane (i.e., dike wall) in a) a biaxial stress system, and b) triaxial stress system. Modified from Davidson and Park (1978).

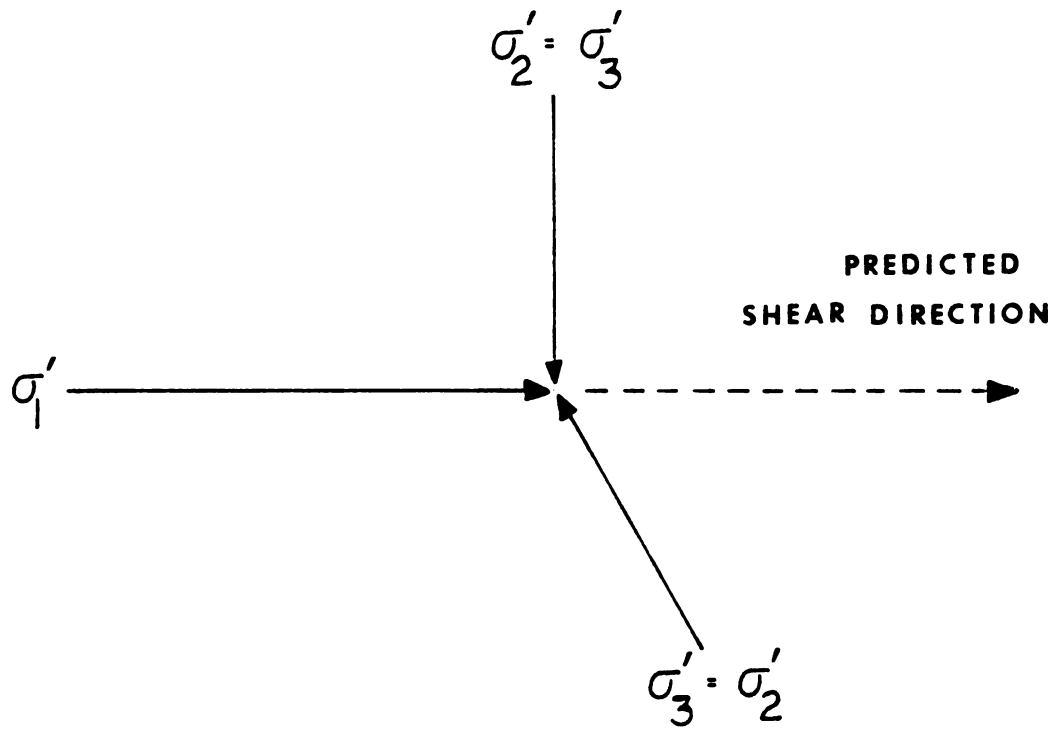
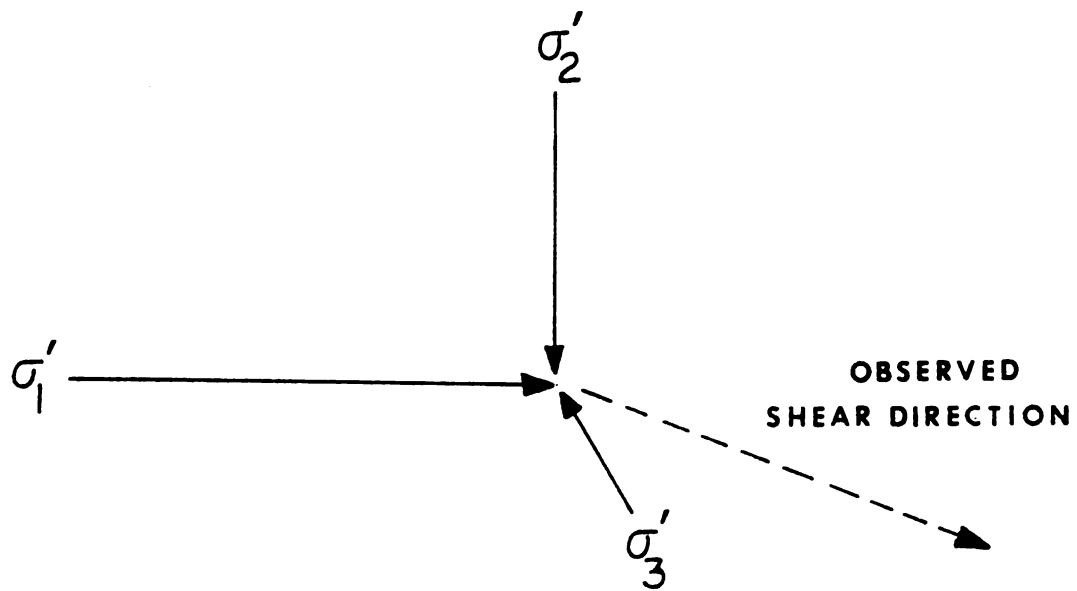
A**B**

FIGURE 14

In a departure from the methods of Berger (1971) and Davidson and Park (1978), layer parallel shears are assumed to arise from the gross bodily rotation of the dike. Talbot (1982) explains that the development of an oblique foliation is afforded by external rotation of the dike toward the XY plane of a bulk strain which produces layer parallel shears, which in turn, induces rotation of internal dike features in an opposite sense (Figure 15). As deformation continues poles to dike margins and internal foliation will tend to approach one another during a bulk strain. It is apparent that the poles to dike margins trace paths toward Z or ZY, while poles to the internal foliation trace paths away from Z or ZY. When plotted on a stereogram, poles to internal foliation can be joined by arcs of great circles to poles of the adjacent dike margin to define what Talbot (1982) calls "apparent structural movement paths". He also assumes that the pole to the internal foliation on the apparent structural movement path is closest to Z or ZY after a homogeneous bulk strain.

Talbot's (1982) method is particularly applicable where the country rock fabric and the internal foliation of the dikes are roughly coplanar. Although this is generally not the case in the Marquette-Republic region, it does not completely rule out a bulk strain model. Talbot (1982) suggests that a lack of parallelism between the two opposing foliations may imply 1) the texture or fabric of the country rock was less responsive to strain, and/or 2) the finite strain seen in the rocks may be the result of several increments of strain in a complex strain history.

Figure 15. Diagram illustrating the response of a dike to bulk strain. Large curved arrows illustrate external rotation of the dike toward the XY plane of strain, while small curved arrows denote the opposite rotation of internal planar features. Small straight arrows show the sense of layer parallel shear.

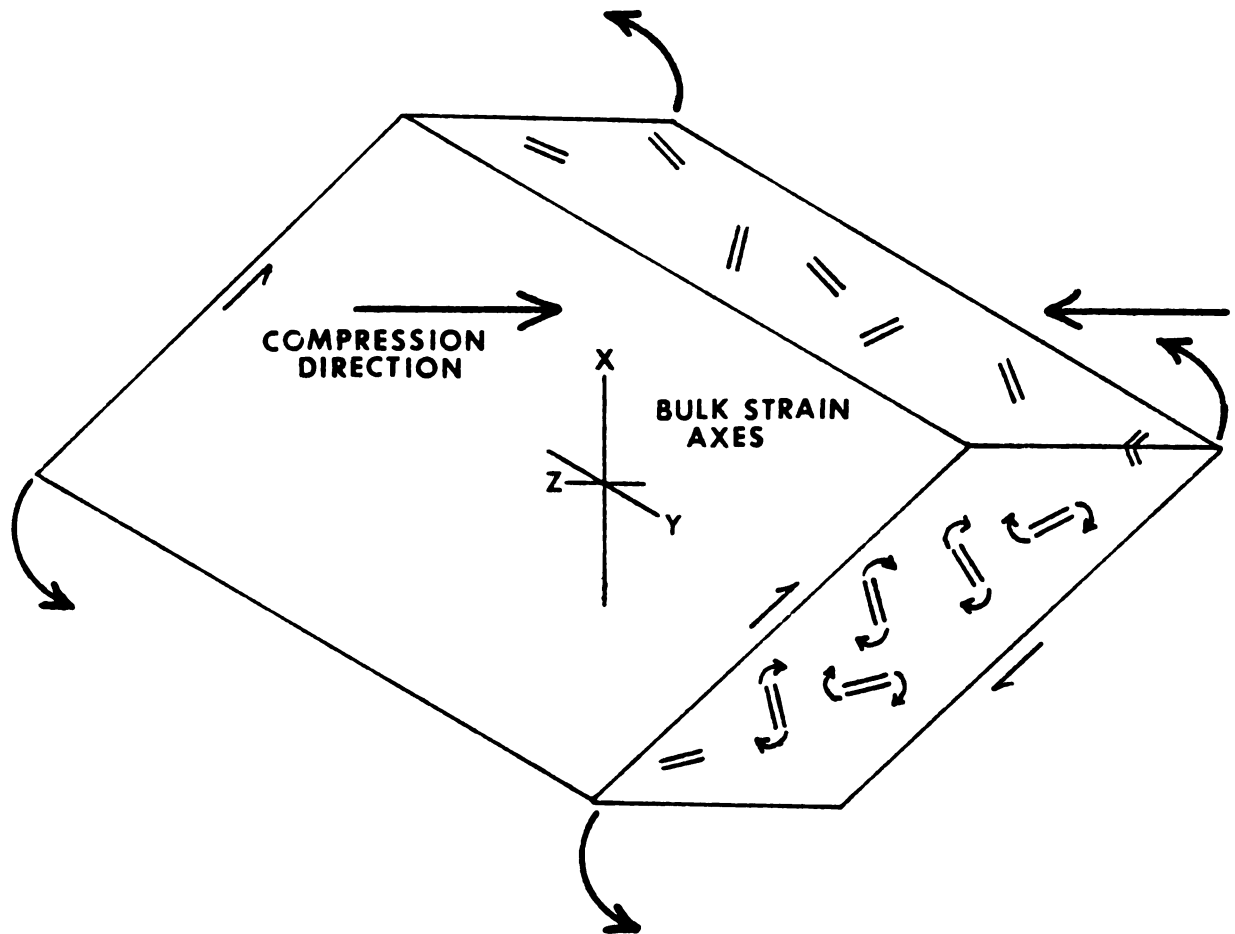


FIGURE 15

RESULTS OF STRUCTURAL ANALYSES

Stress Analysis

The two separate stress analyses of Berger (1971) and Davidson and Park (1978) were applied to data from metadiabase dikes of the four study areas outlined in Figure 2; Republic Trough, Greenwood Reservoir, Michigamme, and Marquette. The analysis of these four areas indicates a different maximum principal stress direction for each area, which is illustrated in Figure 30. In each study area, the derived σ_2 position is near vertical, while σ_1 and σ_3 are near horizontal. However, the σ_1 and σ_3 directions vary across the Marquette-Republic region. Note that the σ_1 direction in each study area is approximately at right angles to the adjacent basement trough region.

Stress analysis of dikes from the Republic Trough area produces Figure 16a, which is a stereoplot (lower hemisphere, equal area projection) with the distribution of σ_1 , σ_2 , and σ_3 positions derived by employing Berger's (1971) method. Positions of calculated mean vectors for each group of stress orientations is also indicated. The resultant stress pattern indicates a near horizontal east-northeast plunging σ_1 , and a north-northwest shallowly plunging σ_3 . The Greenwood Reservoir area produces a similar stress pattern (Figure 16b), but in this study area the σ_1 direction has a more northeast-southwest trend. Analysis of the Michigamme area results in a derived σ_1 position which trends almost due northeast-southwest (Figure 16c). Analysis of the Marquette area (Figure 16d) produces a change in the stress pattern from the previous three. Figure 16d again shows σ_1 and σ_3 to be near horizontal and σ_2 near vertical; however, the maximum principal stress direction is trending almost north-south.

Figure 16. Stereoplot of the derived positions of σ_1 (●), σ_2 (○), and σ_3 (X) from each study area; A) Republic Trough, B) Greenwood Reservoir, C) Michigamme, and D) Marquette. Calculated mean positions for each group are indicated by the appropriate symbol.

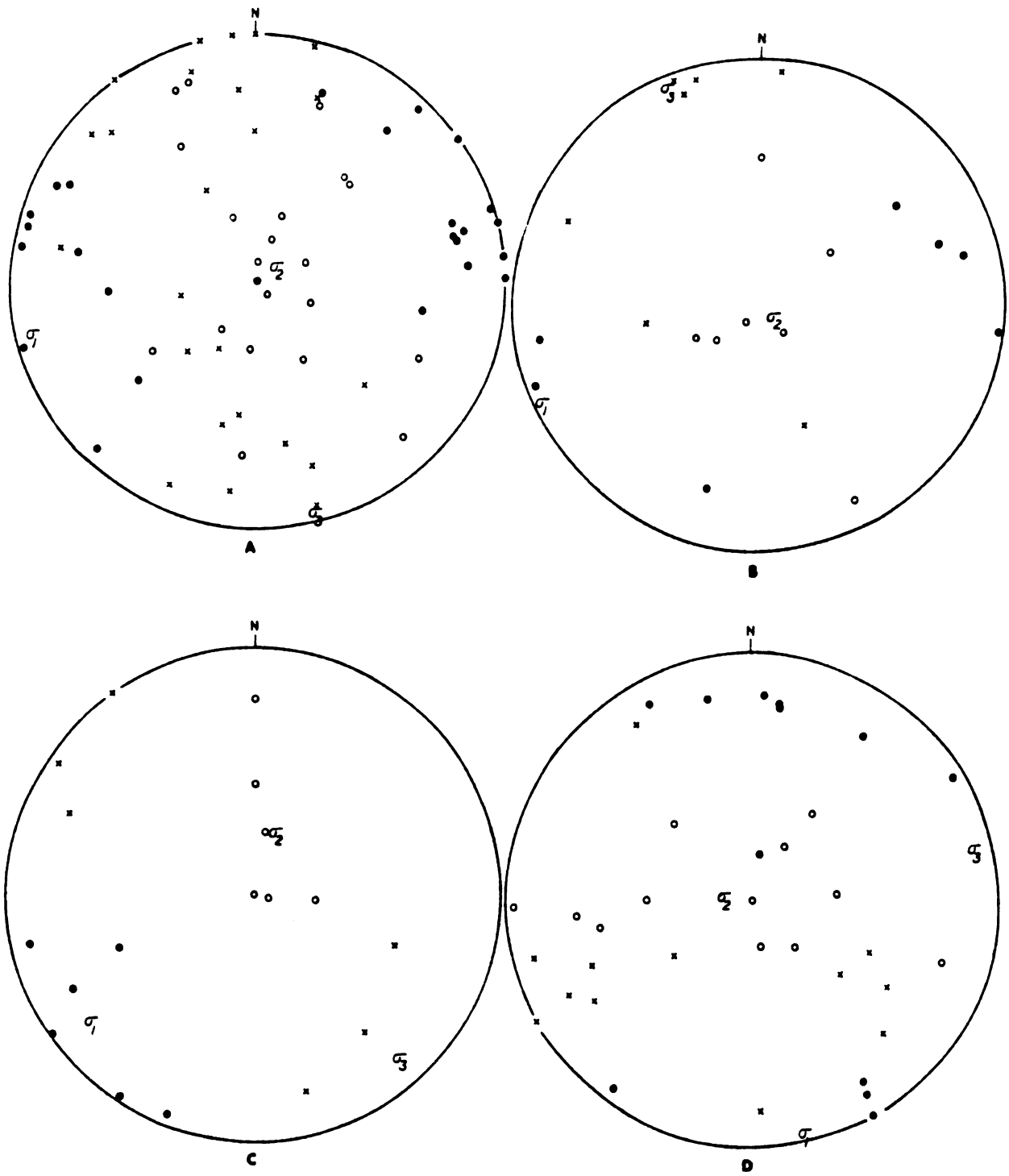


FIGURE 16

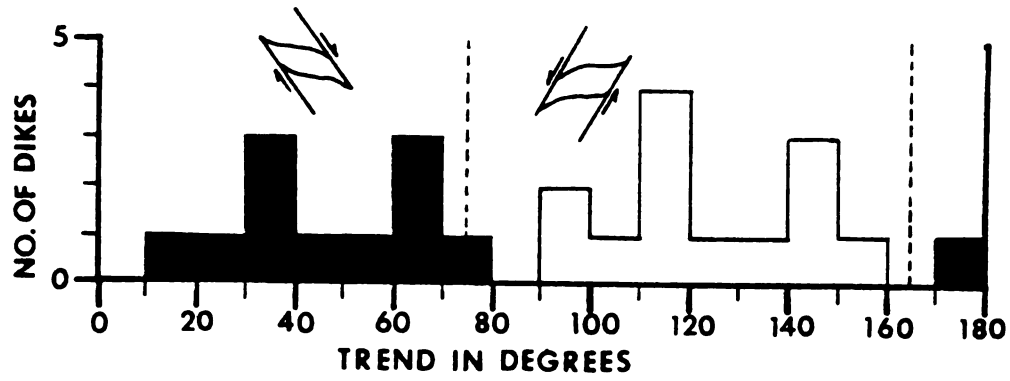
The excellent exposure along highway M-95 and the large basement outcrops north of the city of Marquette allowed the study of diversely oriented dikes which were easily applied to Berger's (1971) method of analysis. This was not the case in the Greenwood Reservoir and Michigamme areas which puts severe limitations on the validity of this method at these locations.

It is thought that slip occurs only along planes oriented such that the critical resolved shear stress is exceeded. Theoretically, this should occur most effectively when σ_1 makes an angle of 45° to the slip plane resulting in the maximum resolved shear stress (Carter and Raleigh, 1969). The wide range of sheared dike orientations in the Republic Trough area indicates that not all can be explained by a theoretical angle of 45° to σ_1 . It is conceivable that smaller magnitudes of shear could occur on dikes that make a smaller or larger angle than 45° to σ_1 , as long as the critical resolved shear stress is exceeded. The fairly wide scatter of the principal stress directions suggests that not all of the sheared dikes made an angle of 45° to σ_1 , and is evidence that the derived stress pattern is clearly dependent upon dike orientation. However, Berger's (1971) method may offer a good approximation in the Republic Trough and Michigamme study areas where there is a fairly wide distribution of dike orientations.

The method of stress analysis introduced by Davidson and Park (1978) is independent of dike orientation and can be used to determine the stress pattern produced by two different stress models: 1) a biaxial system ($\sigma_1 > \sigma_2 = \sigma_3$), and 2) a triaxial system ($\sigma_1 > \sigma_2 > \sigma_3$). The results of these analyses are represented in Figures 17 through 21.

The trend of σ_1 and the $\sigma_2\sigma_3$ plane can be somewhat defined by 1) histograms (Figures 17-20) showing changes from dextral to sinistral horizontal shear, and 2) the accompanying stereoplots (Figures 17-20) showing poles to sheared dikes divided into quadrants of dextral and sinistral sense of

Figure 17. Republic Trough - A) Histogram defining the change from dextral to sinistral sense of shear. B) Stereoplot of poles to sheared dikes with the best fit position of the plane of no shear (—) and the plane of no horizontal shear (---).



A

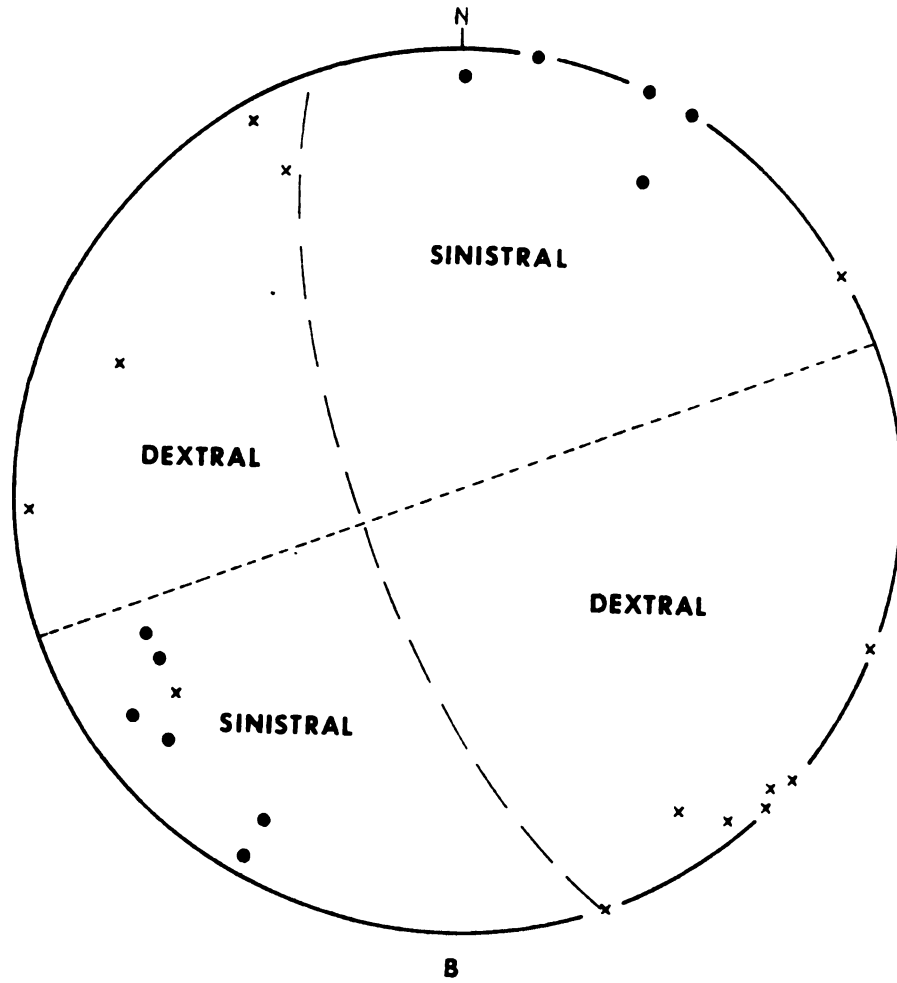


FIGURE 17

Figure 18. Greenwood Reservoir - A) Histogram defining the change from dextral to sinistral sense of shear. B) Stereoplot of poles to sheared dikes with the best fit position of the plane of no shear (—) and the plane of no horizontal shear (---).

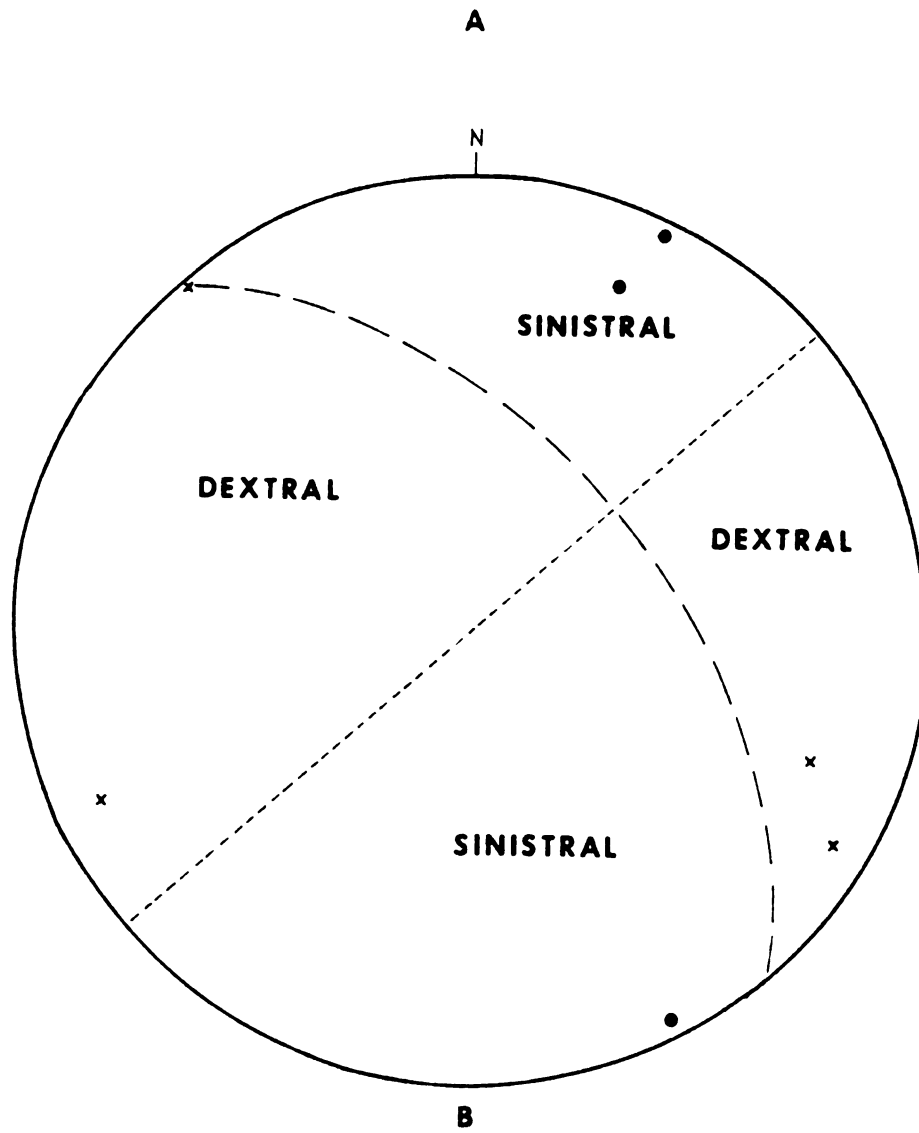
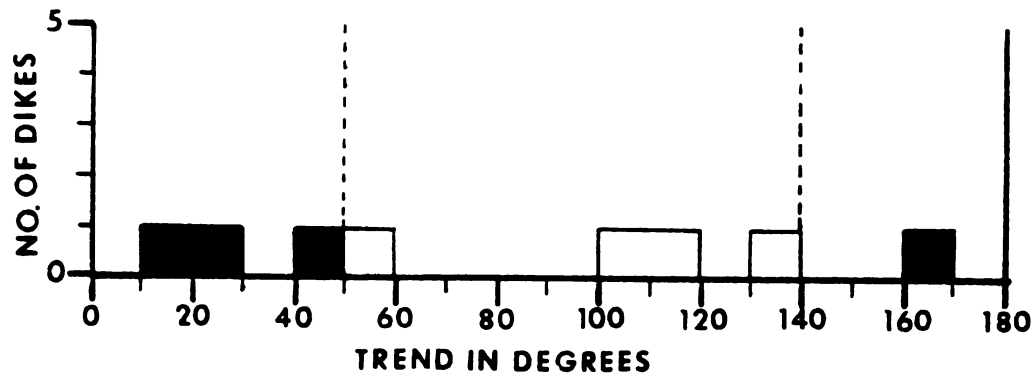
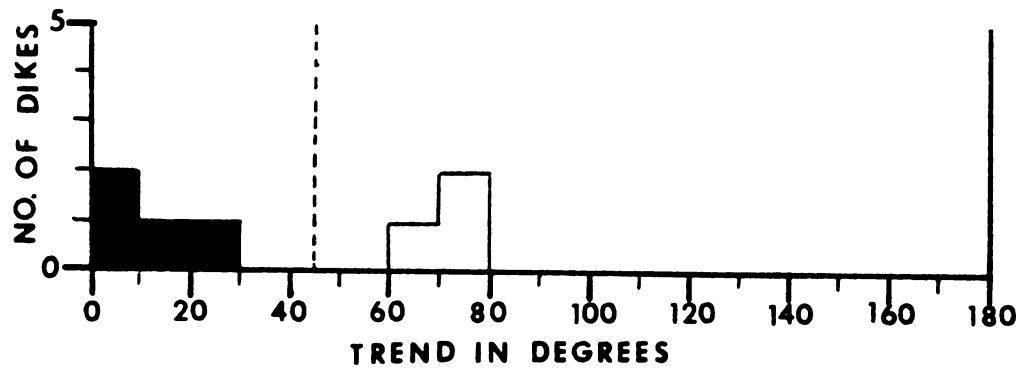
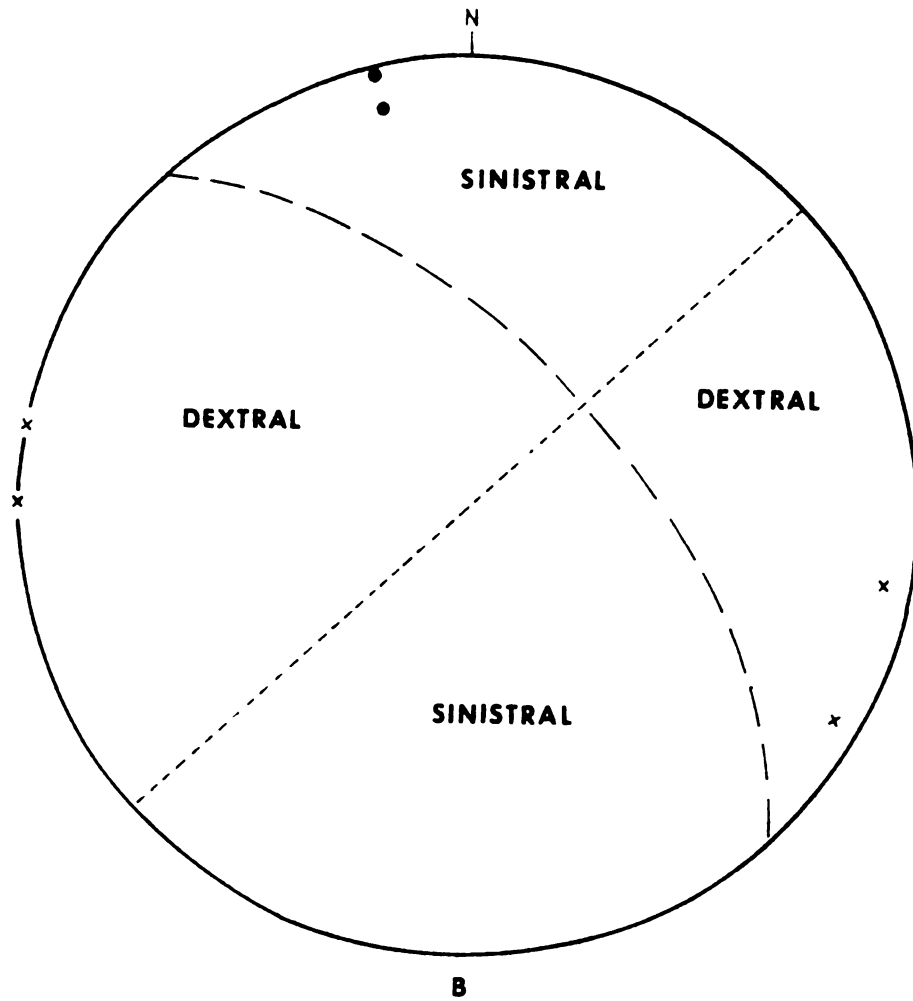


FIGURE 18

Figure 19. Michigamme - A) Histogram defining the change from dextral to sinistral sense of shear. B) Stereoplot of poles to sheared dikes with the best fit position of the plane of no shear (—) and the plane of no horizontal shear (---).



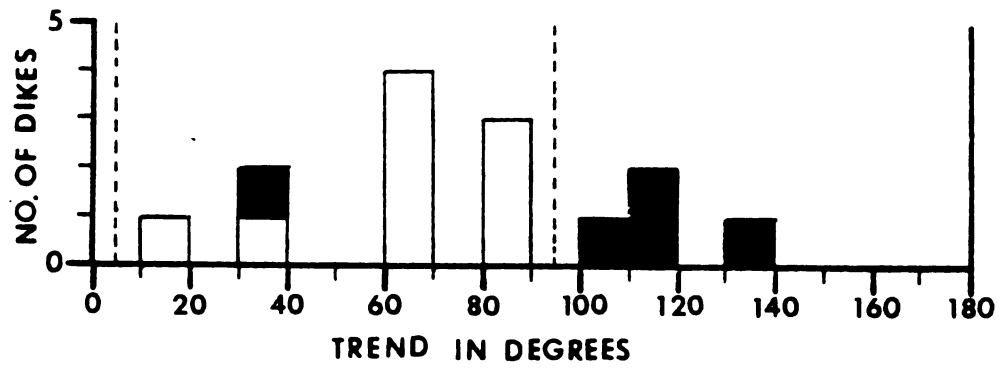
A



B

FIGURE 19

Figure 20. Marquette - A) Histogram defining the change from dextral to sinistral sense of shear. B) Stereoplot of poles to sheared dikes with the best fit position of the plane of no shear (—) and the plane of no horizontal shear (---).



A

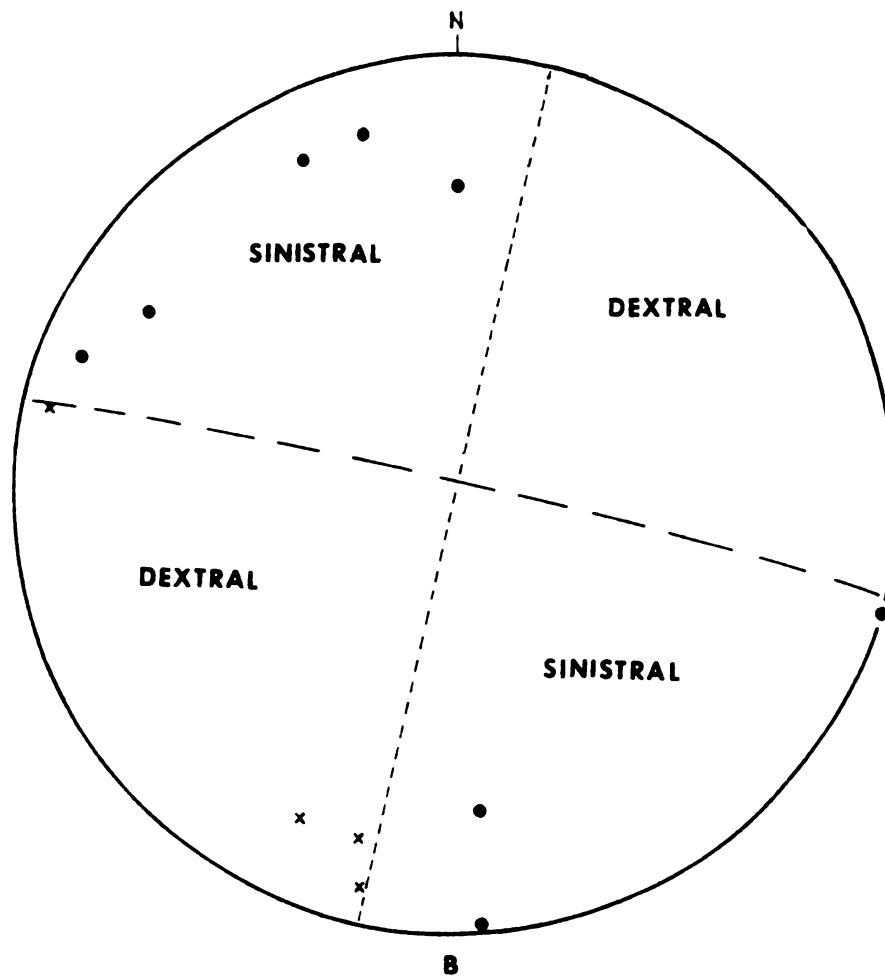


FIGURE 20

horizontal shear. As in the results using Berger's (1971) method, there is a change in the σ_1 orientation from east-northeast at Republic to nearly northeast-southwest at Michigamme and the Greenwood Reservoir to approximately north-south in the Marquette area. The vertical component of shear is represented predominantly by reverse slip, indicating that σ_1 is near horizontal but offering little help in constraining the maximum principal stress direction.

Analysis for a triaxial stress system should not only help constrain the stress pattern, but also offer a more realistic paleo-stress system. Davidson and Park (1978) have stated that when $\sigma_1 > \sigma_2 > \sigma_3$ the shear direction moves away from the predicted shear direction for a biaxial $\sigma_1 > \sigma_2 - \sigma_3$ system. This movement is always toward the σ_3 shear component on the shear plane (Figure 14). Likewise, points X and Y lying on the $\sigma_2\sigma_3$ plane represent movement from X to Y toward σ_3 in a triaxial stress system. The foliation/dike wall intersection is taken to approximate the intermediate stress axis, although not necessarily paralleling it as in Berger's (1971) method. A review of the field data from all four areas indicates this intersection is generally steeply plunging. This suggests that rotations of X to Y (i.e., the rotation of a point on the $\sigma_2\sigma_3$ plane toward σ_3) will be toward the primitive, and an aid in defining the stress pattern for each study area.

Figure 21 shows stereograms from the four study areas with the positions of σ_1 and the $\sigma_2\sigma_3$ plane. The looped arrows represent movements X and Y and attempt to constrain the position of σ_1 on a best fit basis. A review of the stereograms shows that the vast majority of X to Y rotations are toward the primitive, indicating that σ_3 is near horizontal in all four cases. The trend of σ_1 in each case closely parallels those derived through Berger's (1971) method;

Figure 21. Stereograms of the four study areas; A) Republic Trough, B) Greenwood Reservoir, C) Michigamme, and D) Marquette, with position of σ_1 and the $\sigma_2\sigma_3$ plane.

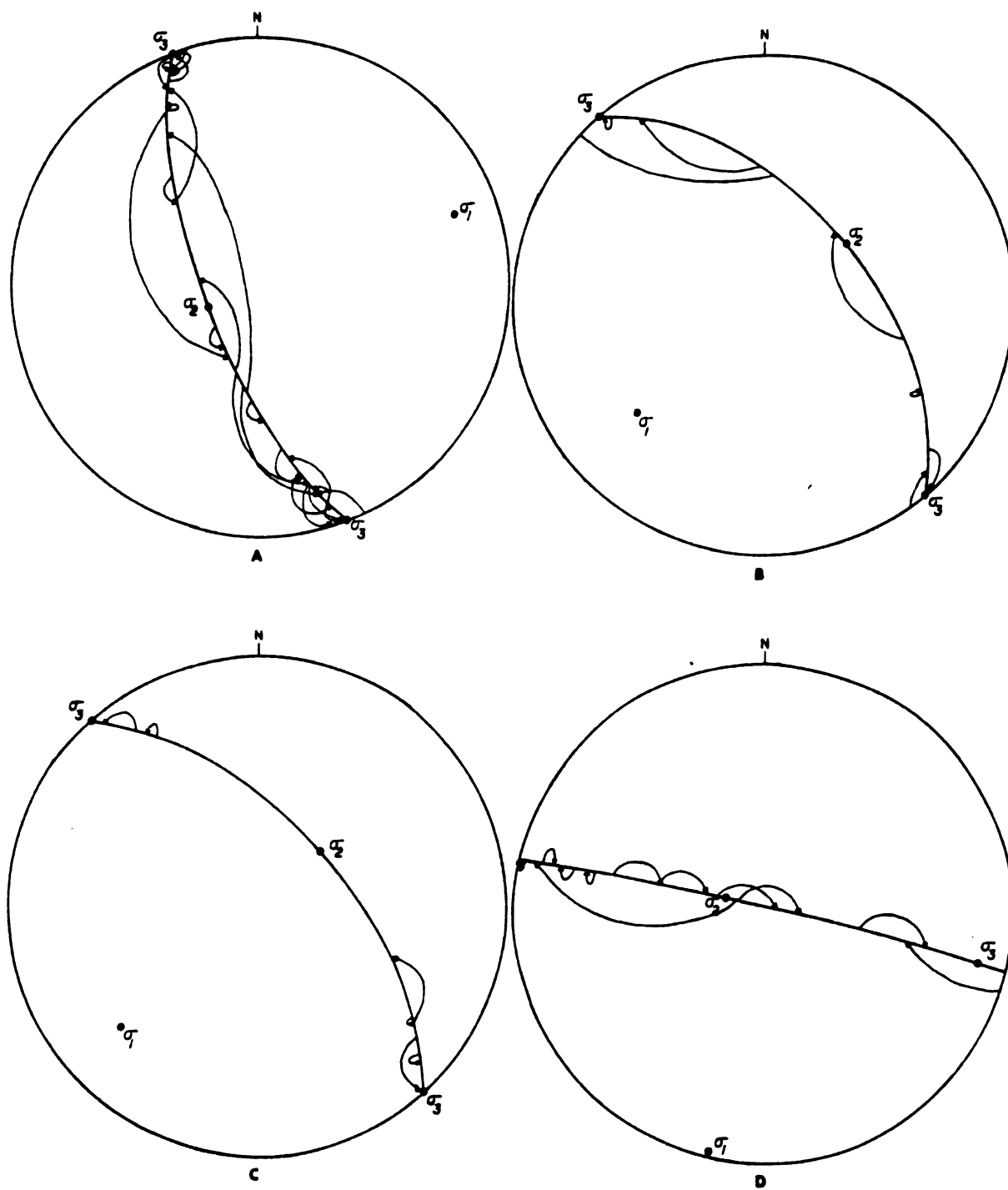


FIGURE 21

however, in all but the Marquette area the plunge of σ_1 is slightly steeper when derived by the method of Davidson and Park (1978).

The difficulty in applying this method to this set of data lies in the fact that the general dip of the sheared dikes is near vertical, leaving few poles near the center of the stereoplot to constrain the dip of the $\sigma_2\sigma_3$ plane prior to analysis by a triaxial stress system. This lack of sufficient data forces a derivation of the σ_1 position in a triaxial stress system to be based on the assumption that σ_3 is near horizontal, and may account for the slight variability in results between the methods of Berger (1971) and Davidson and Park (1978).

Assuming no volume change, Ramsay and Graham (1970) have shown that deformation confined to a discrete zone where the host rock remains relatively undeformed, as in the case here, must be accomplished by simple shear. Both Berger (1971) and Davidson and Park (1978) suggest that simple shear is the dominant mechanism in the formation of obliquely foliated dikes. In so doing, and as a requirement for stress analysis, it must be assumed that the dikes have not undergone rotation. This illustrates the limitation in using such strain features in the derivation of principal stress directions. However, this limitation is lessened in the Marquette-Republic region due to a lack of sufficient field evidence, such as folded dike margins and/or a parallelism of dike and granite gneiss foliation, that might suggest the dikes had undergone gross bodily rotation.

Strain Analysis

The general strain analysis used in this study was introduced by Talbot (1982). In this analysis, incompetent single layers (i.e., dikes) are thought to deform with the more competent country rocks in a regional bulk strain by undergoing gross bodily rotation, resulting in layer parallel shear. Smith (1975, 1977) has suggested that incompetent layers parallel to the principal planes of

strain should shorten by 1) thickening, and 2) the development of mullioned structures (i.e., inverse boudinage) and having undergone little, if any, bodily rotation. However, these type of structures which would support a bulk strain model are not found here.

Throughout the four study areas the dikes display internal foliations oblique to both their own margins and the host granite gneiss foliation. Figure 22 shows poles to the foliation within planar elements of dikes in the Republic Trough, Greenwood Reservoir, Michigamme, and Marquette areas. The poles are tied by arcs of great circles to the poles of the accompanying dike margins and represent what Talbot (1982) has termed "apparent structural movement paths". These apparent structural movement paths are thought to represent the rotation of the dike contacts driving the rotation of any internal features between them in an opposite sense. The sheet margins and internal foliation therefore tend to approach one another from opposite directions during a bulk strain (Figure 15). Referring to Talbot's (1982) method, the pole to the internal foliation is here thought to lie at the end of the apparent structural movement path closest to Z or ZY of the strain ellipsoid. It is apparent that since the tie lines in Figures 22a-22d do not fit a single structural movement pattern, a single bulk strain can be ruled out.

Inspection of the data suggests that three sets of tie lines fitting three different movement scenarios could be present. These are shown separately in Figures 23a, 23b, and 23c. The percentage of data fitting each pattern from the four study areas is shown Table 1. Figure 23d shows apparent structural movement paths which fit none of the three patterns. Some of these have been found to come from near where displaced felsic sheets cut across foliated metadiabase dikes. The felsic sheets can be considered an internal feature of the metadiabase dikes, and like the internal foliation, should rotate

Figure 22. Stereoplot of poles to the foliation (open circles) within planar elements of dikes tied by arcs of great circles to the poles of the accompanying dike margins (arrowheads) in A) Republic Trough, B) Greenwood Reservoir, C) Michigamme, and D) Marquette study areas.

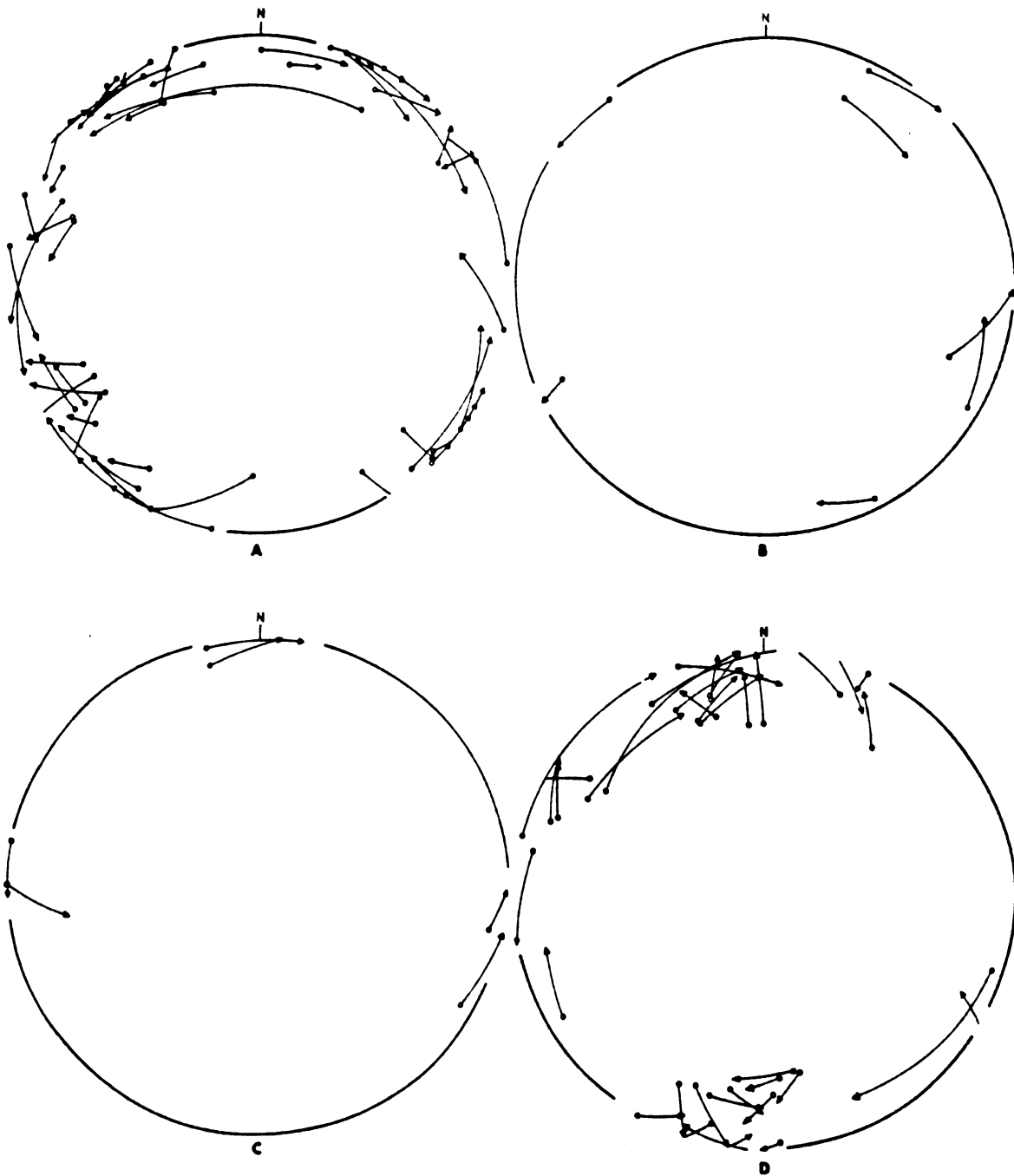


FIGURE 22

Figure 23. Three patterns (A, B, and C) defined by the apparent structural paths from all four study areas. Figure D shows apparent structural movement paths which fit none of the three patterns. Dashed planes represent the best fit position of the principal planes with the principal strain axes labelled.

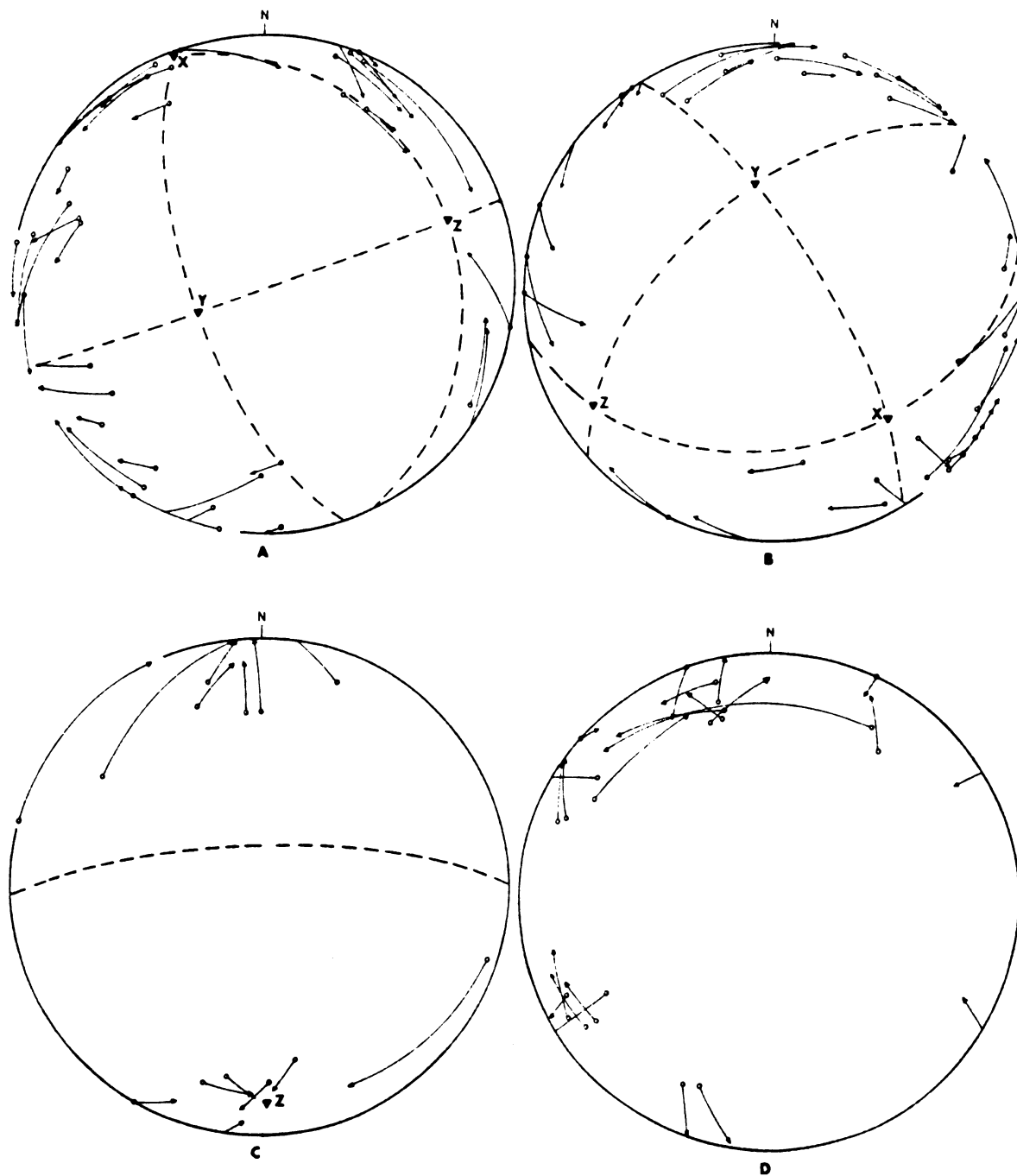


FIGURE 23

Table 1. Percentage of apparent structural movement paths from each study area which are found on the four stereograms of Figure 23.

	Figure A	Figure B	Figure C	Figure D
Republic Trough	49	42	0	8
Greenwood Reservoir	43	43	0	14
Michigamme	17	83	0	0
Marquette	15	9	40	36

anthithetically with respect to the metadiabase dike margins as the dike rotates. However, the felsic sheets may have been less responsive to rotation and thus may have affected (i.e., retarded) the rotation of the adjacent internal foliation, thus producing very local variations in the regional strain. However, the majority of anomalous apparent structural movement paths in Figure 23d cannot readily be explained by pure shear.

The apparent structural movement paths in Figure 23c are parts of great circles converging in a Z axis that plunges shallowly to the south, and could be the result of a uniaxial flattening strain (i.e., pure shear). In Figures 23a and 23b, the tie lines converge on a Z axis plunging shallowly to the east-northeast and southwest, respectively. The principal planes are clearly defined and the X and Y axes have been assumed based on the results of petrographic analyses discussed earlier.

Closer inspection of the strain patterns reveals that each is controlled by apparent structural movement paths within dikes from only one or two of the study areas (Table 1). The strain pattern of Figure 23a appears to be controlled by tie lines from dikes in the southern part of the Republic Trough area and bordering the north margin of the Republic Trough proper. It is interesting to point out that the derived σ_1 direction of this area (Figure 21a) is nearly identical to the Z direction. The strain pattern represented by Figure 23b is apparently controlled by tie lines from dikes in the Michigamme area and the northern reaches of the Republic Trough area (i.e., near the south margin of the Marquette Trough). The derived σ_1 direction (Figure 21c) for the Michigamme area closely parallels this Z direction. The pattern in Figure 23c is entirely controlled by apparent structural movement paths in the Marquette area, and its Z direction is similar to the derived σ_1 of this same study area (Figure 21d).

In considering a bulk strain model for the deformation of the dikes, the three movement patterns could be taken to represent three separate noncoaxial increments of strain. The north-south Z direction shown in Figure 23c for the Marquette area agrees with the maximum shortening direction found by Westjohn (1978) in a strain study of the Kona Formation in the eastern part of the Marquette Trough, and could represent the final increment of strain in a complex strain history. The above discussion would require that different areas of the Marquette-Republic region undergo shortening perpendicular to local maximum shortening directions, either at the same time or at different times during the deformation. This would result in an extremely complex strain history which could not easily be explained.

An analysis of the foliated dikes based upon a regional bulk strain model is ruled out due to: 1) the lack of sufficient field evidence which would support such a bulk strain, and 2) the large number of apparent structural movement paths that cannot be explained by pure shear. The fact that structural movement paths have been derived and show a variation in the strain pattern across the Marquette-Republic region might suggest that there was a small component of pure shear involved in the deformation of the basement. However, it is thought that the primary mechanism of deformation was by simple shear, and any pure shear component may be considered negligible.

SHEAR STRAIN - A FUNCTION OF DIKE ORIENTATION AND STRESS DIRECTION

It has been noted that shear strain increases as the angle between the dike margin and internal foliation becomes smaller (Ramsay and Graham, 1970). In addition, Carter and Raleigh (1969) and Watterson (1968) have stated that slip will most likely occur along planes that make an angle of 45° to σ_1 , thereby exceeding the critical resolved shear stress. Assuming both of the above statements are true, a direct relationship should exist between the shear strain and the angle of the dike to σ_1 .

Figure 24 is a plot showing the dihedral angle between the dike margin and the internal foliation versus the angle between the dike wall and the derived maximum principal stress (MPA) of its respective study area. Sheared dikes from all four study areas have been used in this plot. Since shear strain varies within individual dikes from the margin to the center, measurements from only the dike margins were used for this comparison.

The general pattern produced indicates that dikes oriented near 45° to σ_1 have undergone relatively higher magnitudes of shear strain than those making smaller or larger angles with σ_1 . This suggests that during deformation the dikes of the four study areas responded similarly with respect to the local maximum principal stress of their respective areas.

Figure 24. Dihedral angle between dike margin and internal foliation versus the angle between the dike wall and derived σ_1 (angle from MPS) from sheared dikes in all four study areas. Best fit curve is a 2nd order polynomial with a correlation coefficient of 0.582 computed by linear regression.

□ REPUBLIC TROUGH
 ○ GREENWOOD RESERVOIR
 △ MICHIGAMME
 ◇ MARQUETTE

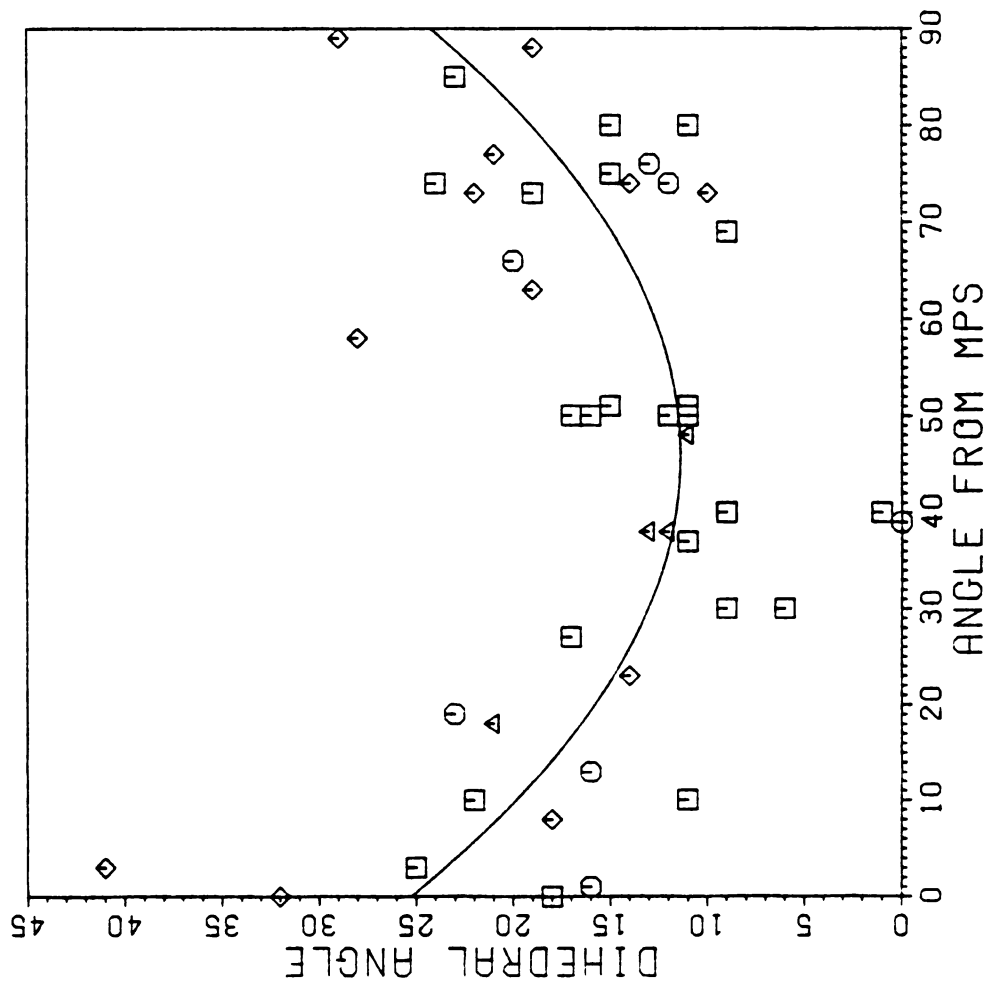


FIGURE 24

DISCUSSION

Stress analysis of the four study areas defines local variations in the regional stress and suggests that the local strain variation may be a response to this stress variation. The general pattern (σ_1 and σ_3 horizontal, σ_2 vertical) is consistent, but variations in the bearing of the σ_1 and σ_3 axes are clearly evident. Figure 25 shows the derived maximum principal stress directions superimposed across boundaries of the adjacent basement troughs. It appears from the diagram that this variation may be attributed to the "concentration" of a regional stress on the local irregularities within the basement (i.e., troughs), much the same way that stress concentrates at right angles around a hole in an elastic plate under stress.

Experimental and theoretical work on "stress concentration" has primarily been dealt with in materials research. Roark (1943) termed such local irregularities as "stress raisers". Figure 26 is a photoelastic diagram illustrating the stress concentration introduced by a local irregularity within a plate, thus modifying the otherwise simple stress distribution (Petersen, 1974). It is not suggested that the deviation of the stress pattern around the Marquette and Republic troughs would mimick that illustrated in Figure 25. It is only presented as an example of how a stress pattern can be modified by local irregularities within a plate. Applied to this case, basement troughs have produced a concentration of a regional stress nearly perpendicular to their boundaries. It should be pointed out that the derived σ_1 directions for the Republic Trough, Greenwood Reservoir, and Michigamme areas do not make an angle of exactly 90° to the adjacent trough margin, whereas the Marquette area σ_1 direction is almost exactly normal to the adjacent trough margin. A single

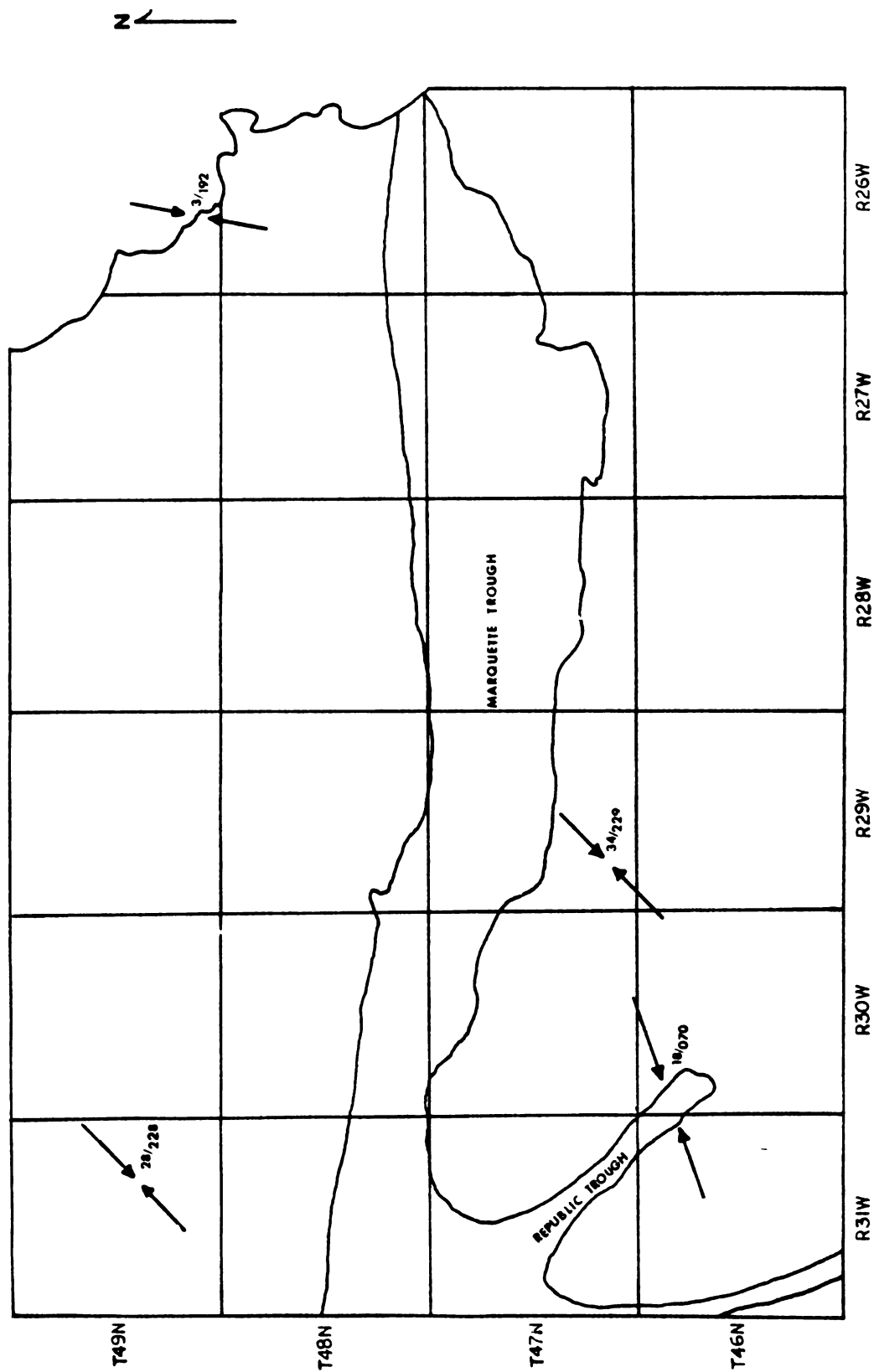


Figure 25. Derived σ_1 directions (plunge/plunge direction) for each study area.



Figure 26. Stress concentration introduced by a notch (local irregularity) within a plate under stress. Photoelastic diagram is from Peterson (1974).

isolated irregularity or hole is generally thought to produce a greater effective stress concentration than a number of similar holes placed close together (Peterson, 1974). This may help explain the apparently greater stress concentration in the Marquette area. The Republic Trough, Michigamme, and Greenwood Reservoir areas may have undergone less effective stress concentration due to the close proximity of the western Marquette Trough and the Republic Trough.

The model proposed is a regional stress pattern with severe local deviations due to basement irregularities and resultant stress concentration. This stress concentration results in what are considered high strain zones (troughs) separated by large, intervening basement highs. Tightly folded and faulted trough metasediments have been found to have undergone up to 45% horizontal shortening normal to the trough margins during the Penokean Orogeny (Westjohn, 1978).

Although the basement may have undergone a comparatively low amount of homogeneous strain, it is apparent that it was involved in the deformation via localized high strain zones (i.e., sheared dikes). This agrees with the model proposed by Cambray (1978) for the deformation of the Marquette-Republic region during the Penokean Orogeny. Cambray (1978) suggests that movement within the basement along discrete high shear strain zones allowed closure of the basement troughs during compression, thus controlling the deformation of the MRS within the troughs. The results of this study seem to support this model, as evidenced by the concentration of derived σ_1 directions within the basement at nearly right angles to the trough margins and its geometric relationship of strain features within the trough sediments.

If closure of the trough margins is to be envisaged as the controlling mechanism in the deformation of the MRS, the intervening basement blocks must

have undergone a fairly substantial amount of shortening. A review of observed shear directions shows that the majority (approximately 57% have shallow plunges ranging between 0° and 30° , while less than 15% have plunges greater than 60° and none greater than 72° and indicates that shortening within the basement was largely the result of horizontal shear. It should be noted that the vertical component of shear, in the vast majority of dikes shows evidence of reverse sense of shear which also agrees with a shortening of the basement.

A stress concentration on the basement troughs, as discussed earlier, might suggest that sheared dikes near trough margins would show evidence of greater effective shortening in the form of 1) a larger component of vertical shear, and 2) comparatively higher shear strains, than sheared dikes farther from trough margins. However, shear directions and their plunges do not indicate a direct relationship with their proximity to trough margins. This suggests that the sheared dikes (as a group) behaved somewhat homogeneously, in the sense that their relative magnitude of shear strain seems to have been controlled solely by their geometric relationship to the local maximum principal stress direction.

CONCLUSIONS

It is concluded that movement has occurred within the Precambrian W basement of the Marquette-Republic region of Northern Michigan during the Penokean Orogenic Event. This movement has taken the form of shear along the margins of Proterozoic metadiabase dikes, such that the dikes acted as zones of weakness within the otherwise rigid basement. Results of structural analyses indicate simple shear deformation (i.e., no dike rotation) and, for the most part, rule out a bulk strain deformation.

In addition, the following conclusions are drawn from this study:

- 1) Different stress patterns were derived from the structural analysis of metadiabase dikes for each study area. This stress pattern variation shows that in each study area the derived σ_1 is nearly perpendicular to the trend of the adjacent trough margin and indicates that deformation within the basement was dependent upon the nature (trend) of the basement troughs. This is thought to be the result of stress concentration about these irregularities (troughs) within the basement.
- 2) There is an excellent correlation between structural features measured in the field and under the microscope. A variation in the measured finite strain pattern across individual dikes indicates a higher magnitude of shear strain near dike margins than in dike interiors. This is supported by the relatively greater degree of hornblende preferred orientation near the margins.
- 3) Dikes oriented 45° to σ_1 show evidence of having undergone a relatively greater amount of shear strain than dikes oriented less than or greater than 45° to σ_1 . This shows that the deformation of the dikes was in large part dependent upon their geometric relationship to the local σ_1 .
- 4) The study supports a basement control model for the deformation of the overlying metasediments.

The results of this study highly support the model proposed by Cambray (1978) whereby movement within the basement along discrete planes has afforded the closure of the Marquette and Republic trough margins, thus controlling the deformation of the MRS within the troughs. It is clear that the Precambrian W basement has undergone some degree of shortening, however, the magnitude is not known and would be a logical next step for the further study of the basement in this region.

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