This is to certify that the

thesis entitled

The Role of Volume Loss in the Development of Deformation Fabrics in Proterozoic Metadiabase Dikes in the Marquette-Republic Region of Northern Michigan

presented by

Thomas Lynn Weaver

has been accepted towards fulfillment of the requirements for

Masters degree in Geological Sciences

Major professor

Date 1/19/94

THE ROLE OF VOLUME LOSS IN THE DEVELOPMENT OF DEFORMATION FABRICS IN PROTEROZOIC METADIABASE DIKES IN THE MARQUETTE-REPUBLIC REGION OF NORTHERN MICHIGAN

By

Thomas Lynn Weaver

A THESIS

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

MASTER OF SCIENCE

Department of Geological Sciences

1994

ABSTRACT

THE ROLE OF VOLUME LOSS IN THE DEVELOPMENT OF DEFORMATION FABRICS IN PROTEROZOIC METADIABASE DIKES IN THE MARQUETTE-REPUBLIC REGION OF NORTHERN MICHIGAN

By

Thomas L. Weaver

Foliated Lower-Proterozoic metadiabase dikes intrude Archean granite-gneiss and greenstone terranes, and Lower-Proterozic metasediments in Marquette County. These dikes are cut by non-foliated Keweenawan diabase dikes, suggesting that foliation is related to Penokean orogenic events. Intensity of foliation increases and the angle between dike wall and margin decreases, from dike interior to dike margin, indicating substantially higher shear strain at the margins. Shear strain may result in volume loss (solution transfer) in addition to bulk-rock material transport. Similar chemical trends from dike interior to margin are observed in most dikes, decreasing CaO, Na_2O, and Al_2O_3. Wall rock contamination appears negligible, with possible exception of K_2O in two dikes.

Based on chemical and petrographic data, it appears that strain-induced volume loss occurred, primarily as a result of plagioclase dissolution, although it was probably not significant enough to account for pervasive foliation observed in the dikes.

ACKNOWLEDGEMENTS

I wish to express deep gratitude to Dr. Bill Cambray, chairman of my thesis committee, whose knowledge and continuous input made this thesis and my career in geology a reality. Special thanks to the other committee members, Dr. Tom Vogel, whose courses and critical guidance provided me the knowledge of igneous and metamorphic systems necessary to complete this study, and Dr. Duncan Sibley for helpful suggestions throughout the study and critical review of the final manuscript.

Thanks also to Dr. David Westjohn, whose friendship, guidance, knowledge of the Marquette-Republic region, and knowledge of field geology, are greatly appreciated.

My field work was funded through Geological Society of America Grant #4830-91 and is gratefully acknowledged at this time. The Officer-in-Charge at the United States Coast Guard facility at Lighthouse Point graciously gave permission to remove the samples necessary to complete the study, even though requests to sample at this site are normally denied.

My fellow students at the Geology Club helped make MSU very enjoyable, particularly Tom Sabin and Chris Christensen. Special thanks to Kris Huysken, whose unfailing support, advice, encouragement, and friendship made the completion of this project possible.

The Geology Department staff was a tremendous help during my stay, thanks to Loretta, Cathy, Jackie, Diane, and Bob.

Thanks also to Steve Smith, a very great friend, who has twice encouraged me to leave the security of an excellent job at the railroad to return to academia.

My deepest gratitude is to my family. They have given me the skills necessary to succeed in my many endeavors, with special encouragement throughout my educational career. My wife, Dawn, has never quit believing in me and I owe my success to her undying support. I wish that my father, Robert Weaver, had survived to see me graduate and to fly fish, I know that he would be very proud.

TABLE OF CONTENTS

LIST OF TABLES.. vii

LIST OF FIGURES...viii

INTRODUCTION.. 1

REGIONAL GEOLOGY.. 6

THE ROLE OF VOLUME LOSS................................. 13

APPLICABILITY OF VOLUME LOSS TECHNIQUES IN
THE STUDY OF SHEARED METADIABASE DIKES.................. 18

SAMPLING AND METHODS.................................... 21

- Loss on Ignition Analysis.......................... 26
- Petrographic Analysis.............................. 26
- Shear Strain Analysis.............................. 26
- X-Ray Fluorescence................................. 27
- Methods for Identifying Wall Rock Contamination.... 28

COMPARISON OF LIGHT VERSUS DARK MINERALS................ 31

RESULTS OF LOSS ON IGNITION ANALYSIS.................... 32

RESULTS OF PETROGRAPHIC ANALYSIS........................ 34

ANALYSIS OF SHEAR STRAIN................................ 60

RESULTS OF X-RAY FLUORESCENCE ANALYSIS.................. 70

THE EFFECT OF SHEAR STRAIN ON BULK-ROCK CHEMISTRY....... 98

DISCUSSION.. 106

CONCLUSIONS... 111

REFERENCES.. 113

APPENDIX 1. Results of XRF analysis of
samples from Republic area dike 1......... 117

TABLE OF CONTENTS (continued)

APPENDIX 2. Results of XRF analysis of samples from Republic area dike 2......... 118

APPENDIX 3. Results of XRF analysis of samples from Republic area dike 3......... 119

APPENDIX 4. Results of XRF analysis of samples from Republic area dike 4......... 120

APPENDIX 5. Results of XRF analysis of samples from Republic area dike 5......... 121

APPENDIX 6. Results of XRF analysis of samples from east-west dike at Lighthouse Point....................... 122

APPENDIX 7. Results of XRF analysis of samples from north-south dike at Lighthouse Point....................... 123

LIST OF TABLES

Table 1.	Comparison of light and dark minerals from samples of Republic area dikes 1, 3, and 4	31
Table 2.	Results of loss-on-ignition procedure for samples from Republic area dikes 1, 3, and 4	33
Table 3.	Modal analysis of Republic area dike 1	41
Table 4.	Modal analysis of Republic area dike 2	44
Table 5.	Modal analysis of Republic area dike 3	47
Table 6.	Modal analysis of Republic area dike 4	50
Table 7.	Modal analysis of Republic area dike 5	52
Table 8.	Modal analysis of Lighthouse Point east-west dike	54
Table 9.	Modal analysis of Lighthouse Point north-south dike	58
Table 10.	Comparison of shear strain values for Republic area dikes 1, 2, and 5. Angle θ' is the angle measured from dike margin to line of maximum extension (foliation)	65

LIST OF FIGURES

Figure 1.	Geologic sketch map of the western Upper Peninsula of Michigan. (Modified from Gair and Thaden, 1968)	2
Figure 2.	Photograph of Republic dike 5, illustrating sigmoidal foliation (highlighted in red)	2
Figure 3.	Map of the Marquette-Republic study area showing Republic area and Lighthouse Point sampling locations	22
Figure 4.	Geologic map of Lighthouse Point, Marquette, Michigan, showing sampling locations. (Modified from Gair and Thaden, 1968)	23
Figure 5.	Sketch of Republic area dikes 1 and 2, which outcrop approximately 12 m apart, with an opposite sense of shear	25
Figure 6.	Photograph of portion of outcrop illustrated in Figure 8, showing Republic area dike 2 and granite-gneiss country rock	25
Figure 7.	Photomicrograph of amphibole from dike center sample, displaying curved cleavage traces, bent crystal boundaries, and radial extinction	36
Figure 8.	Photomicrograph of amphibole from dike interior sample, showing alteration to chlorite and biotite	36
Figure 9.	Photomicrograph showing coarse, twinned, sericitic plagioclase, which may be a remnant of original igneous texture, dike center sample	37

LIST OF FIGURES (continued)

Figure 10.	Photomicrograph showing coarser, euhedral amphibole and biotite surrounded by fine-grained groundmass, dike center sample.............	40
Figure 11.	Photomicrograph of elongate fibrous mat of very fine mica, and coarser chlorite and biotite, dike center sample....................................	45
Figure 12.	Photomicrograph of fabric in dike margin sample, euhedral biotites displaying primary foliation (horizontal) and superimposed crenulation cleavage (semi-vertical, sigmoidal bands)...........................	48
Figure 13.	Photomicrograph of altered pyroxene, with significant alteration to opaque minerals. Surrounding grains display remnant igneous textures...................	56
Figure 14a.	Diagram illustrating the geometry of a typical shear zone in heterogeneous rocks...	62
Figure 14b.	Diagram illustrating the geometry of a typical shear zone in homogeneous rocks...	62
Figure 15.	Diagram illustrating the relation of the strain ellipse to shear in the sample shear system....................	67
Figure 16.	Diagram illustrating a graphical approximation of total displacement (g units) for dike 2 by finding the area under the strain/distance curve.......	67
Figure 17a.	Plot of SiO_2 vs. distance from dike margin for Republic area dikes.............	73
Figure 17b.	Plot of SiO_2 vs. distance from dike margin for Lighthouse Point dikes..........	73
Figure 18a.	Plot of Al_2O_3 vs. distance from dike margin for Republic area dikes.............	74
Figure 18b.	Plot of Al_2O_3 vs. distance from dike margin for Lighthouse Point dikes..........	74

LIST OF FIGURES (continued)

Figure 19a. Plot of FeO vs. distance from dike margin for Republic area dikes............. 75

Figure 19b. Plot of FeO vs. distance from dike margin for Lighthouse Point dikes.......... 75

Figure 20a. Plot of MgO vs. distance from dike margin for Republic area dikes............. 76

Figure 20b. Plot of MgO vs. distance from dike margin for Lighthouse Point dikes.......... 76

Figure 21a. Plot of CaO vs. distance from dike margin for Republic area dikes............. 78

Figure 21b. Plot of CaO vs. distance from dike margin for Lighthouse Point dikes.......... 78

Figure 22a. Plot of Na_2O vs. distance from dike margin for Republic area dikes............. 79

Figure 22b. Plot of Na_2O vs. distance from dike margin for Lighthouse Point dikes.......... 79

Figure 23a. Plot of K_2O vs. distance from dike margin for Republic area dikes............. 81

Figure 23b. Plot of K_2O vs. distance from dike margin for Lighthouse Point dikes.......... 81

Figure 24a. Plot of TiO_2 vs. distance from dike margin for Republic area dikes............. 82

Figure 24b. Plot of TiO_2 vs. distance from dike margin for Lighthouse Point dikes.......... 82

Figure 25a. Plot of P_2O_5 vs. distance from dike margin for Republic area dikes............. 83

Figure 25b. Plot of P_2O_5 vs. distance from dike margin for Lighthouse Point dikes.......... 83

Figure 26a. Plot of MnO vs. distance from dike margin for Republic area dikes............. 84

Figure 26b. Plot of MnO vs. distance from dike margin for Lighthouse Point dikes.......... 84

Figure 27a. Plot of Cr vs. distance from dike margin for Republic area dikes............. 86

LIST OF FIGURES (continued)

Figure 27b. Plot of Cr vs. distance from dike margin for Lighthouse Point dikes.......... 86

Figure 28a. Plot of Ni vs. distance from dike margin for Republic area dikes............. 87

Figure 28b. Plot of Ni vs. distance from dike margin for Lighthouse Point dikes.......... 87

Figure 29. Plot of Cu vs. distance from dike margin for Lighthouse Point dikes.......... 89

Figure 30a. Plot of Zn vs. distance from dike margin for Republic area dikes............. 90

Figure 30b. Plot of Zn vs. distance from dike margin for Lighthouse Point dikes.......... 90

Figure 31a. Plot of Rb vs. distance from dike margin for Republic area dikes............. 91

Figure 31b. Plot of Rb vs. distance from dike margin for Lighthouse Point dikes.......... 91

Figure 32a. Plot of Sr vs. distance from dike margin for Republic area dikes............ 92

Figure 32b. Plot of Sr vs. distance from dike margin for Lighthouse Point dikes......... 92

Figure 33a. Plot of Y vs. distance from dike margin for Republic area dikes............ 93

Figure 33b. Plot of Y vs. distance from dike margin for Lighthouse Point dikes......... 93

Figure 34a. Plot of Zr vs. distance from dike margin for Republic area dikes............ 94

Figure 34b. Plot of Zr vs. distance from dike margin for Lighthouse Point dikes......... 94

Figure 35a. Plot of Nb vs. distance from dike margin for Republic area dikes............ 96

Figure 35b. Plot of Nb vs. distance from dike margin for Lighthouse Point dikes......... 96

Figure 36a. Plot of Ba vs. distance from dike margin for Republic area dikes............ 97

LIST OF FIGURES (continued)

Figure 36b.	Plot of Ba vs. distance from dike margin for Lighthouse Point dikes.........	97
Figure 37.	Plot of major-oxides vs. shear strain, Republic dike 1...........................	101
Figure 38.	Plot of major-oxides vs. shear strain, Republic dike 2...........................	102
Figure 39.	Plot of major-oxides vs. shear strain, Republic dike 5...........................	105

INTRODUCTION

Strain can be described in terms of translation, rotation, distortion, and dilation (also known as dilatation), collectively known as kinematics. For structural geologists, the most difficult of the four movements to prove is dilation, which is a net change in volume. Historically, most workers have interpreted strain indicators such as slaty cleavage, to be the result of a distortion-type strain, such as flattening. These studies frequently noted little or no change in volume. The apparent lack of a known mechanism to remove the material, lack of a place to dispose of large amounts of material, and absence of applicable finite strain gauges are all reasons volume loss has been largely neglected in past studies (Wright and Platt, 1982).

The Marquette-Republic region of Michigan's Upper Peninsula (Figure 1) is primarily comprised of two major Archean basement-rock units known as the Southern and Northern complexes (Van Hise and Bayley, 1897). Metadiabase dikes and sills of six ages intrude basement rocks throughout the region (Baxter and Bornhorst, 1988). Many of the dikes are Post-Archean (Lower Proterozoic) in age, as evidenced by relatively linear boundaries against the

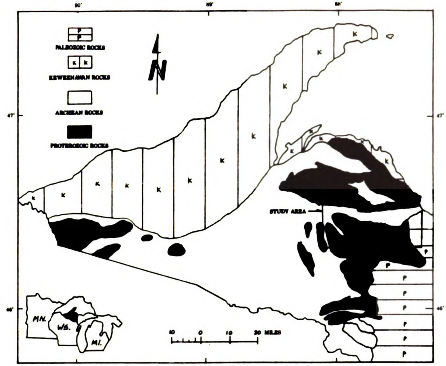


Figure 1.--Geologic sketch map of the western Upper Peninsula of Michigan. (Modified from Gair and Thaden, 1968).

Figure 2.--Photograph of Republic area dike 5, illustrating sigmoidal foliation (highlighted in red).

surrounding country rock. Some dikes intrude the lower part of the Lower Proterozoic Marquette Range Supergroup (Cannon and Gair, 1970) metasediments, which were deformed in the Penokean Orogeny. Original igneous textures are commonly absent in foliated Lower Proterozoic dikes, although they are common in younger, non-foliated Keweenawan (Upper Proterozoic) dikes (Baxter and Bornhorst, 1988). The foliation prevalent in many Lower Proterozoic dikes is attributed to the Penokean Orogeny. In other studies of sheared dikes, the presence of oblique foliation has been attributed to layer-parallel shear along the dike margin (Miller, 1945; Berger, 1971; Talbot, 1982; and others). During the Penokean Orogeny, the dikes of the Marquette-Republic region probably acted as ductile-shear zones, while the surrounding country rock remained fairly rigid. As evidence of this, dike foliation is non-parallel to country rock foliation, with the exception of an area several centimeters wide at the dike margin (Myers, 1984). Most foliation of the Southern complex granite-gneiss is attributed to Archean deformation.

The foliation of Lower Proterozoic dikes in the Republic area is typically visible in outcrop, as a sigmoidal pattern (Figure 2). Differential mineral weathering has accentuated the foliation on this outcrop. The dihedral angle measured between the dike margin and line of maximum extension (trend of the foliation) within the shear zone is small at the dike margin, indicative of very-high shear strain, and large in the dike interior, indicating much lower shear strain.

Ramsay and Graham (1970) studied shear zones in limestone, metagabbro, and felsic rock, demonstrating that schistosity first appeared as planar structures oriented at approximately 45 degrees to the margins of the shear zone, becoming more pervasive toward the center of the shear zone. As the degree of schistosity increased, the angle of the schistosity with the shear zone margins (dihedral angle) decreased. These observations would be analogous to changes in foliation noted in the Republic area dikes.

Ramsay and Huber (1983) noted that mineral alignment in shear zones is parallel to the line of maximum extension, with minimal shape change in the areas of least strain, and maximal shape change in areas of highest strain. It may be expected that Penokean-age deformation of the Lower Proterozoic diabase dikes was accompanied by deformation and recrystallization of minerals in low-strain regimes. In higher-strain regimes, deformation may have resulted in several episodes of recrystallization and solution transfer (volume change) of some materials, e.g. SiO_2, CaO, and the alkalis into/out of the dikes.

The objective of the study is the investigation of potential volume loss in the dikes. The study compares textural, mineralogical, and chemical data from low-strain regimes (dike interiors) with data from high-strain regimes (dike margins). A complete suite of samples was analyzed petrographically and chemically by X-ray fluorescence. The study also compared foliated dikes from the Republic Trough area with non-foliated, but highly-altered dikes from Lighthouse Point in Marquette. The Republic area dikes intrude the granite-gneiss of the Southern Complex, while the Lighthouse Point dikes intrude the mafic Mona Schist, allowing a direct comparison of mafic and felsic wall-rock types. Samples from several dikes were analyzed for water content, to compare mineral hydration of high and low-strain regimes.

REGIONAL GEOLOGY

The Marquette-Republic region of Michigan is comprised of rock units ranging in age from 3.2 Ga to approximately 1.9 Ga (Sims, 1976; Van Schmus, 1976; Sims and Peterman, 1983). A tonalite-gneiss unit in Watersmeet, which is south of the study area, has been dated 3.4 Ga (Peterman and others, 1980). This unit is similar to gneiss found throughout the study area. The surface appearance of much of the region is typical of the southern Canadian Shield, with infrequent bedrock outcrops, and a thin veneer of glacial debris.

The region was thrust into national prominence in 1844 with the discovery of large quantities of high-grade iron ore, at the present day location of the city of Negaunee. Sporadic discoveries of copper, lead, silver, and gold in the region continued throughout the late 1800's.

As a consequence of the mineral wealth of the region, much of the geology has been understood since the turn of the century, primarily through the early work of Van Hise and Bayley (1897) and Van Hise and Leith (1911). Since that time, large areas of the region have been investigated and mapped in detail by the U.S. and Michigan Geological Surveys. The Marquette Range Supergroup (Cannon and Gair,

1970) sedimentary package, which contains the economic deposits of banded iron formation, is particularly well documented. Cambray (1984) includes a comprehensive list of references which led to the present understanding of the geology of the region.

The geology of the region is divided by the east-west trending Marquette Trough. The area south of the trough, which is known as the Southern Complex, is comprised of a migmatite gneiss unit, and a younger gneiss unit that also includes coarse-grained granites. Various ages have been assigned to the Southern Complex, ranging from the currently accepted 3.5-2.8 Ga (Sims and Peterman, 1983) to >2.6 Ga (Cannon and Simmons, 1973; Van Schmus and Woolsey, 1975). Radiometric dating in the Southern Complex is difficult because of widespread disturbance in the isotopic systems (Sims and Peterman, 1983). The area north of the Marquette trough, which is known as the Northern Complex, is comprised of eight meta-igneous units and two metasedimentary units dated 2.75-2.6 Ga (Peterman, 1979). A large portion of the Northern Complex, immediately north of the Marquette Trough, is a greenstone terrane. The prolific pillow basalts and interflow sediments of this part of the complex are the result of underwater vulcanism. The Northern Complex Gneiss is a tonalite and quartz monzonite unit that includes migmatitic gneiss similar to migmatite gneiss found in the Southern Complex.

The Archean basement is unconformably overlain by the Lower Proterozoic Marquette Range Supergroup (Marquette Range Supergroup is hereafter referred to as MRSG), which was deposited between 2.5-1.9 Ga (Sims, 1976; Van Schmus, 1976). The MRSG, which has been correlated with Animikie Group in Minnesota and Ontario (Morey, 1973), is comprised of three groups, Chocolay, Menominee, and Baraga, and several individual formations, consisting of clastic and carbonate sediments and mafic and felsic volcanics. Within the study area, the MRSG is primarily confined to the steep-sided, fault-bounded Marquette and Republic Troughs. Each of the three MRSG groups consist of a basal conglomerate and quartzite unit overlain by a transgressive sequence, which Cambray (1984) and others have interpreted as multiple episodes of crustal instability. The MRSG thickens to the south, which Cambray (1978) attributed to rifting along the southern margin of the craton. The Chocolay Group seems to represent widespread progressive subsidence and near-shore sedimentation, while the Menominee Group appears to represent sedimentation in a more localized environment, confined primarily to the fault-bounded troughs. The sedimentation rate appears to have kept pace with the rate of subsidence in the Chocolay and Menominee Groups, while the Baraga group, with the exception of the basal Goodrich Quartzite, represents a period of regional subsidence, with a thick sequence of deeper-water turbidites (Cambray, 1984).

All rock units in the study area are metamorphosed, with metamorphic grade varying from widespread lower-greenschist facies to amphibolite facies at a metamorphic node centered near Republic (James, 1955). The source of the metamorphism is interpreted as two orogenic events; the Algoman Orogeny at approximately 2.7 Ga (Sims and others, 1980), which resulted in remobilization of the Archean basement; and the Penokean Orogeny, having an approximate age of 1.89-1.82 Ga (Hoffman, 1988), which deformed the MRSG sediments as well as the dikes described in this study. It is possible that a third metamorphic event impacted the region. The Keweenawan rifting (1.1-1.0 Ga) resulted in the eruption of at least 300,000 km^3 of flood basalts into the Lake Superior Basin from a area as close as 100 km to the Marquette-Republic region (BVTP, 1981). It is probable that this event thermally overprinted previous metamorphic signatures in the region. The tectonic forces associated with the initial rifting and consequent thrust-reactivation of the Keweenaw Fault may have impacted the Marquette-Republic region as well.

Mafic dikes, sills, and other tabular intrusive bodies outcrop in many locations within the study area. These intrusives range in size from <0.5 m to hundreds of meters in width, such as the sill that forms the north wall of the Republic Iron Mine. Although the intrusives of this study are limited to Lower-Proterozoic diabase dikes, a brief review of the findings of Baxter and Bornhorst (1988) is included to simplify the complex relations of the various intrusions.

Most studies have assigned three broad ages to these intrusives which are sufficient for most discussions; Archean, Lower Proterozoic, and Keweenawan. Baxter and Bornhorst (1988) utilized petrographic differences and cross-cutting relationships to suggest a minimum of six intrusive events. The Northern Complex greenstone belt contains the oldest mafic intrusions. These are cut by plutons ranging in composition from gneissic tonalite to granodiorite, which in turn are cut by amphibolitic units in the vicinity of Wetmore's Landing. The two oldest groups of intrusives pre-date the culmination of Archean orogenic events. The next intrusive activity post-dates the Archean Orogeny and pre-dates the deposition of the MRSG. Baxter and Bornhorst (1988) and other workers interpret these dikes as equivalents to the Archean Matachewan Dike swarm in Ontario, which have an age of approximately 2.6 Ga. The next group of intrusives are the Lower Proterozoic dikes which are the subject of this study. These intrusives cut the Chocolay, Menominee, and the lower part of the Baraga Group. While the intrusives of the other five groups appear to have a preferential orientation, the orientation of these dikes is highly variable. The intrusives of this group are variably deformed depending on orientation with respect to Penokean-age stress directions. The fifth and sixth groups of intrusives are Keweenawan in age. The older-Keweenawan intrusives are fine-grained, trend approximately north-south, and are typically less than 30 m in width. The younger-Keweenawan intrusives are medium to coarse-grained, trend approximately east-west, and can be >200 m in width.

There are a number of interpretations of the regional effects of the Penokean Orogeny. Brief reviews of several differing interpretations are included as background material. For details, the reader is advised to consult one of the recent rigorous discussions on the subject.

James's studies of the region from the 1950's provided a interpretation of the depositional environment that has not been significantly altered by subsequent studies. He suggested that compression-controlled basement faulting controlled the deformation of the MRSG, albeit without a plate tectonic driving force.

Cannon (1973) proposed deformation was the result of vertical mobilization of the Archean basement, rather than horizontal tectonics. Cannon suggested that gravity sliding on a northward inclined surface was followed by vertical displacement of fault bounded blocks of Archean basement, giving rise to major basins such as the Marquette and Republic Troughs.

Cambray (1978) proposed a continental collision model. In this model, a southern continent is thought to have overridden the Superior Province resulting in a southward-dipping subduction zone. The Niagara fault zone is proposed to be the suture, and the Menominee River, which follows the fault, forms the geographic border of Michigan and Wisconsin. Cambray (1978) suggests that the absence of arc-type rocks north of the Niagara fault zone, supports a southward-subduction model. He proposed that subduction was terminated by the collision with the southern continent. The subduction and collision would have produced horizontal compression in the Archean basement, causing ductile shear. The horizontal compression may have reactivated the fault-bounded Marquette Trough (interpreted as the Archean-age suture of the Northern and Southern Complexes), and the Republic trough, deforming the MRSG sediments.

More recently, Hoffman (1988) proposed that Penokean deformation was the result of attempted subduction of a passive continental margin during a collision with oceanic crust. This theory interprets the area as a foredeep, resulting from thrust loading of the continental crust, with sedimentation necessarily moving into the basin created by crustal loading and subsidence.

THE ROLE OF VOLUME LOSS

One of the significant tasks facing the structural geologist is the interpretation of data from strain analyses. Specifically, were the observed strain indicators deformed by a constant-volume process, or a volume-reduction process, such as solution transfer?

The role of volume loss in the formation of foliation, cleavage, and other deformation fabrics has been the subject of disagreement within the scientific community since the mid 1800's. Sorby (1853) was the first worker to propose a substantial volume loss. In his study of slates and slaty cleavage, Sorby suggested that volume losses as great as 50% were possible. Several workers, including Fisher (1884) and Becker (1904), were critical of volume reduction, suggesting it was improbable, if not impossible. Perhaps Sorby was influenced by these criticisms and his final conclusion (1908) suggests a volume reduction of only 11%. Some workers including Cloos (1947) and Westjohn (1989) continue to regard volume loss with some skepticism, suggesting that the process is of minimal importance.

Until recently, most volume reduction studies have utilized two or more strain gauges, typically deformed fossils, mineral veins, ferruginous reduction spots, or some other geometric object common in the outcrop being examined (Cloos, 1947; Wright and Platt, 1982; Westjohn, 1989; Wright and Henderson, 1992). The amount of volume loss suggested in these studies is variable, ranging from none (Cloos, 1947; oolites) to 50% (Wright and Platt, 1982; graptolites), and 40%-60% (Wright and Henderson, 1992; worm burrows). In each of these studies, the undeformed dimensions of the strain gauges are assumed. This method is limited to rock units containing quantities of suitable strain gauges, which typically excludes igneous and metamorphic rock units.

Ramsay and Wood (1973) made 990 determinations of strain ellipsoids in slates from slate belts located in Wales, Scotland, Great Britain, Norway, and Vermont. All of the ellipsoids measured were of oblate form, plotting within the flattening field of the deformation plot. The mean ellipsoid was situated on the line separating the fields of true constriction and true flattening. This plot, which suggested a 60% volume change, was rejected as unrealistic. Noting that a sufficient number of points plotted beneath the 20% volume change line, Ramsay and Wood then suggested volume loss of 20%. Subsequent volume loss studies such as Glazner and Bartley's study of Mojave mylonite zones (1991) have shown volume losses as large as 70%.

Wright and Platt (1982) investigated deformation and cleavage development in the Martinsburg Shale formation of the Eastern Appalachians. The Martinsburg shale is thought to be deformed as a result of the Taconic and younger orogenic events, which resulted in the formation being folded, faulted, and cleaved. Graptolite fossils with a known undeformed size and shape were used as finite strain gauges, in addition to bivalves, brachiopods, and calcite veins. The graptolites measured were assumed to have been flattened parallel to bedding as a result of compaction, prior to cleavage development. This study demonstrated that maximum shortening occurred when bedding was at high angles to cleavage, with shortening ranging from near zero at small bedding-cleavage angles to 70% at large bedding-cleavage angles. Wright and Platt (1982) interpreted the shortening to be the result of volume reductions as great as 50%, due primarily to pressure dissolution of quartz, calcite, and phyllosilicate minerals, further suggesting that cleavage formed as a result of mineral dissolution.

The studies of O'Hara (1990) and Glazner and Bartley (1991) approached volume reduction from a geochemical perspective, permitting the analysis of any deformed rock. Each study compared compositional and petrographic differences of deformed and non-deformed rock of the same unit. Both studies showed that increased strain is accompanied by large changes in bulk-rock chemistry, thought to be the result of different solubilities, diffusion rates, and other chemical properties of the mineral constituents.

O'Hara (1990) examined mylonite zones in Grenvillian composition gneisses in two thrust areas of the Blue Ridge, in Virginia and South Carolina. He suggested that these mylonite zones may have originated as solution zones which were weakened sufficiently to shear during regional thrusting. Utilizing mineral fabric and whole-rock chemical and modal analyses, his study suggested that mylonites deformed, by inhomogeneous shortening normal to the trend of the foliation, and shearing, parallel to the trend of the foliation. The study suggested a >60% bulk volume loss, as a result of incongruent dissolution of feldspar (producing mica) and crystal-plastic dislocation creep and flattening of quartz, showing a three-fold enrichment of the immobile trace elements Ti, Zr, Y, P, V, and the REE.

Glazner and Bartley (1991) examined mylonite zones in gneiss and granodiorite in the footwall of the Waterman Hills detachment fault in California. The mylonite zones in this area are thought to have formed during Miocene crustal extension as a result of normal shearing. This study showed a two- to six-fold enrichment of the immobile trace elements Ti, Zr, P, and Cr and large depletions in mobile Si, K, and Rb, interpreted as evidence of a 20-70% bulk volume loss. The study estimated the fluid/rock volume ratio for the system assuming no dissolved silica initially and at least one immobile element. They suggest the large fluid/rock ratios necessary to remove up to 70% of the rock (at estimated temperatures of 300-400°C) imply that the mylonite served as a fluid channel. This also supports O'Hara's (1990) suggestion that the mylonite zones in his study originated as solution zones, prior to deformation.

O'Hara (1990) suggested the rocks in his study were deformed by pure shear, but heterogeneous flattening could also have been produced by simple shear. Glazner and Bartley (1991) noted only a poorly-developed foliation in their study and suggest that pervasive lineation and lack of foliation indicate that strain was constrictional. Their interpretation is unusual because of the combination of large volume loss and constrictional strain.

APPLICABILITY OF VOLUME LOSS TECHNIQUES IN THE STUDY OF SHEARED METADIABASE DIKES

There are similarities between the metadiabase dikes of this study and the mylonites studied by O'Hara (1990) and Glazner and Bartley (1991). In each case, the unit being studied is a discrete highly-deformed zone, surrounded by less-deformed material.

To insure the acceptability of the findings of the study, there are several problems that need to be addressed. Gresens (1967) suggests that the interpretation of changes in elemental concentration is not unique, unless the absolute loss or gain of an element(s) can be determined independently, using knowledge of the relationship between composition changes and volume change that accompanied the process. Gresens also suggests that change in elemental patterns could be interpreted to reflect a constant-volume alteration, should an equal volume of new material be introduced into the system as a replacement for material removed during metasomatism. O'Hara (1990) and Glazner and Bartley (1991) addressed this concern by comparing their samples with known elemental compatibilities of hydrothermal systems. The concentration of conserved elements and depletion of non-conserved elements in their studies were interpreted as the result of bulk-rock volume reduction.

Electron microprobe analyses were not utilized in this initial study, and the absolute loss or gain of an element(s) is unknown. Because of this, results of the study are qualitative.

If volume loss occurred during deformation of the dikes, bulk-rock chemistry should vary from non-deformed to deformed rock. Unlike quartz-rich mylonites of previous studies, the metadiabase dikes of this study are silica-poor (<52%) and quartz-poor (typically <5 modal percent). However, the dikes of the study do contain large quantities of Ca-rich plagioclase, and removal of calcium and alkali's from this system could have been accomplished by passage of hydrothermal fluids through the shear zone, exploiting weaknesses in the crystal structure of the plagioclase, such as twin-planes.

Two common criticisms of volume reduction studies are lack of a mechanism to remove material and a lack of a place to dispose of the material removed (Wright and Platt, 1982). Fluid migration through or along the rock units is typically thought to be the material removal mechanism, but opponents of volume loss argue that fluid migration, capable of removing even 20% volume, may be viewed with skepticism. By comparison, the dikes of this study are small (<4 meters in width), discrete bodies, and the fluid and disposal requirements are proportionately less than those necessary for a larger volume of rock. The discrete contact between the dikes and country rock may have acted as a conduit for transporting the quantities of fluid necessary to dissolve and remove significant quantities of material from the system. Fluids that may have migrated upward along discrete shear zones (diabase intrusions) in the basement rock could have intercepted additional conduits such as faults within the overlying MRSG sediments, but removal of much of the MRSG package by erosion makes this suggestion speculative.

SAMPLING AND METHODS

For the purposes of this study, only those metadiabase dikes that post-date Archean deformation and pre-date the Penokean Orogeny were sampled. Seven Lower Proterozoic dikes in the Marquette-Republic region were sampled for this study (Figure 3). The five Republic area dikes, which are located either side of the Republic Trough, intrude Southern Complex granite-gneiss. These dikes were sampled from road cuts along M-95 to ensure fresh samples with minimal exposure to weathering, as well as ease of sampling. The two dikes at Lighthouse Point in Marquette (Figure 4) intrude the Lighthouse Point member of the upper Mona Schist, a unit of the Northern Complex greenstone belt.

Dikes of varying structural orientations and widths were chosen to provide a representative sampling of Lower Proterozoic dikes in the region. Myers (1984) structural analysis of dikes in the region showed Penokean-age maximum principle stress directions (σ_1) of 18/070 at the Republic Trough, and 03/192 just north of the Marquette Trough at Marquette, and these stress directions were utilized for this study.

The strike of the Republic area dikes ranges from 235° to 357°, dipping at angles ranging from 65° to 89°. The

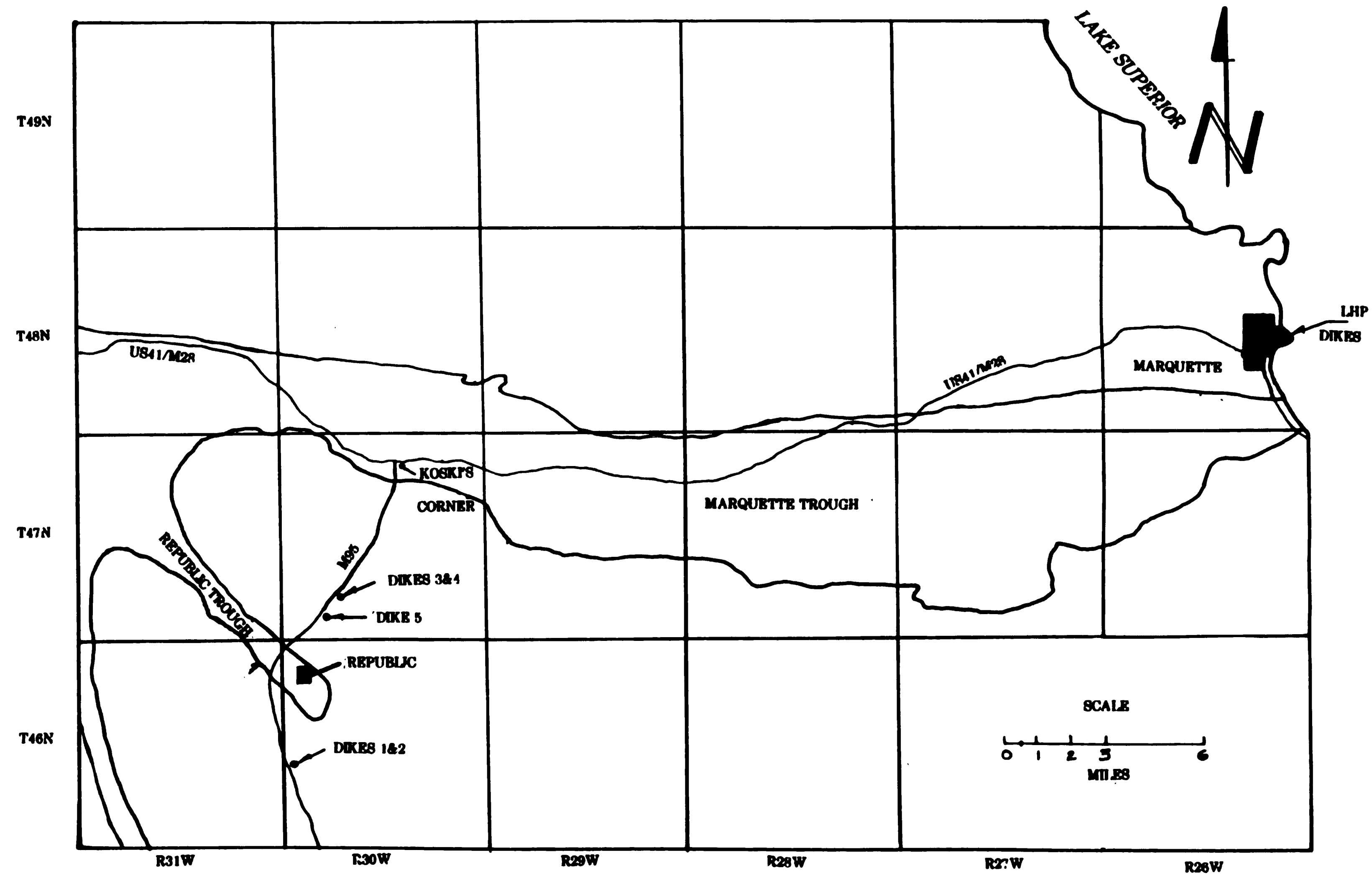


Figure 3.--Map of the Marquette-Republic study area showing Republic area and Lighthouse Point sampling locations.

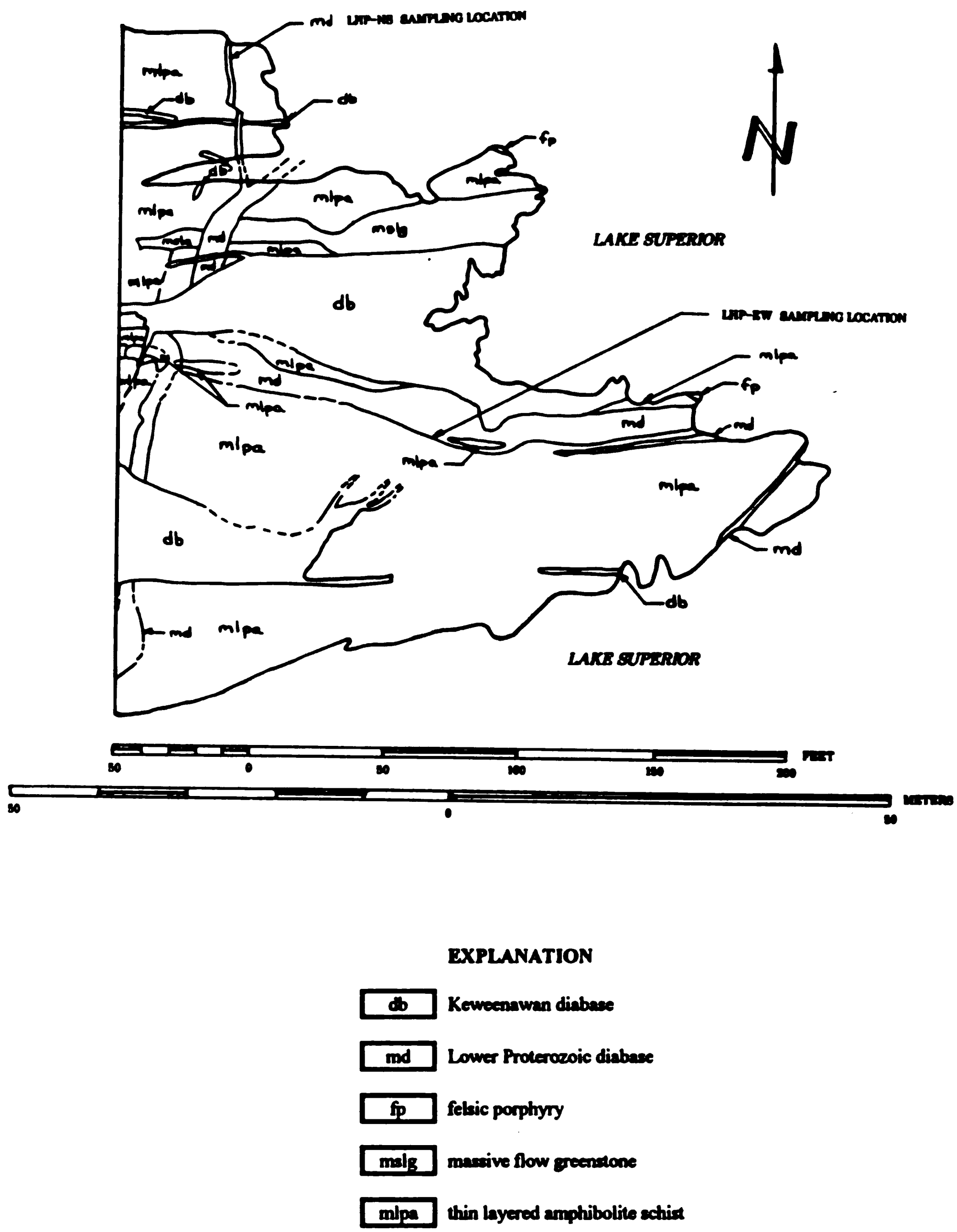


Figure 4.--Geologic map of Lighthouse Point, Marquette, Michigan, showing sampling locations. (Modified from Gair and Thaden, 1968)

sigmoidal foliation visible in the Republic dikes (Figure 2), is assumed to be primarily the result of shearing. Orientation of dikes to the principal stresses appears to have determined the amount and direction of shearing. This is illustrated by Republic dikes 1 and 2, which outcrop 12 m apart (Figure 5). Dike 1, which strikes approximately 235°, was deformed by right-lateral shearing, while Dike 2, which strikes approximately 285°, was deformed by left-lateral shearing. The contact between the Republic dikes and surrounding wall rock is typically straight sided (Figure 6).

James (1955) described an increase in metamorphic grade, from chlorite to sillimanite grade, in the Marquette-Republic region. A sillimanite grade metamorphic node is centered at the Republic Trough. The outer limit of the chlorite grade is approximately 40 miles from the node. The Lighthouse Point dikes (Lighthouse Point is hereafter referred to as LHP) are from the chlorite-grade area, while the Republic dikes are located within the high-grade area (staurolite-sillimanite grade).

Two to five samples from the margin to the interior of each dike, and two samples of surrounding wall rock, were analyzed. Based on results of initial analyses, only dike margin and dike interior samples were analyzed for several of the dikes.

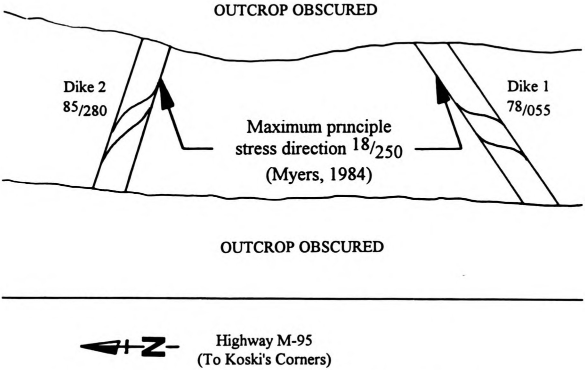


Figure 5.--Sketch of Republic area dikes 1 and 2, which outcrop approximately 12 m apart, with an opposite sense of shear.

Figure 6.--Photograph of portion of outcrop illustrated in Figure 5, showing Republic area dike 2 and granite-gneiss country rock.

Loss on Ignition Analysis

The samples were tested for loss on ignition following the method used by the Geology Division of the Research Council of Alberta. This method determines the loss of H_2O, CO_2, and other volatiles from a rock sample. The use and results of this procedure are discussed in a separate section.

Petrographic Analysis

Thin sections of the samples were prepared and each sample was petrographically analyzed. One thin-section per sample was examined, with the total number of points ranging from 600 to 800. Additionally, a 1000 point count, which compared light (felsic) minerals and dark (mafic) minerals was performed on samples from several dikes. The reader is advised to use caution when interpreting the modal data due to the number of thin-sections examined.

Shear Strain Analysis

Three of the Republic area dikes were selected for shear strain analysis. The angle between the dike margin and the foliation was measured at several locations from the dike margin to the dike interior. The shear strain and displacement of these dikes was calculated using the methods of Ramsay (1967). The results were plotted against select major oxides to show chemical variation as a function of shear strain.

X-ray Fluorescence Analysis

Samples from each dike were prepared for X-ray fluorescence analysis. In this preparation, finely-ground rock sample is allowed to dry at 110°C under a 15 lb. vacuum for 24 hours to remove non-structural water. The samples were processed immediately to avoid rehydration.

The procedure for preparing the glass wafers is as follows: 1.0000 gram of finely-ground sample, 9.0000 grams of lithium tetraborate (flux), and 0.16 grams of ammonium nitrate (oxidizer) were thoroughly mixed in a platinum-gold alloy crucible (all weights +/- 0.0005 g). This mixture was then fired at approx. 1100°C and shaken for 30 minutes. The crucibles were then removed and the contents transferred to a pre-heated platinum-gold alloy mold for 10 minutes of annealing at 550-600°C. The molds were cooled to room temperature and the wafers were removed.

Analyses of major oxides and trace elements (Cr, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, La, and Ba) were collected by an automated Rigaku X-ray fluorescence spectrometer at Michigan State University, using methods described by Mills (1991). Whole-rock standards from the United States Geological Survey were run with each set of samples as known and unknown samples as a means of measuring error. For XRF analyses, whole rock standard errors of less than or equal to 1% were accepted with exceptions. Cu concentrations were generally below XRF detection limits, and errors for La and Ba were generally greater than 10 ppm (Huysken, 1993).

Methods for Identifying Wall Rock Contamination

Several methods were utilized to verify that the observed chemical trends were due to internal changes within the dikes and not outside influences such as wall rock contamination.

Constant Sum Data Effect

Constant sum problems can occur when materials are removed from or added to an otherwise closed-system. Relative quantities of other materials within the system change to reflect these removals or additions. Constant sum problems could be detrimental to studies of volume loss, masking the actual changes that have taken place.

Constant sum data effect can be checked utilizing the methods outlined by Russell and others (1989). Using a computer-generated statistical pick of probable conserved elements, two conserved elements with a common denominator are ratioed against one another. Using this type of plot, changes in the elemental quantities can be verified as real, rather than resulting from a quantity of a particular mineral entering or leaving the system, such as a potassium kick at the margin due to wall rock contamination.

A primary check of the oxides and elements revealed no conserved elements in several of the dikes. The absence of conserved elements negated this procedure.

Wall Rock Contamination in Felsic Terranes

Two samples of wall rock were collected at each dike location, one from the dike margin and another at least 1 meter from the dike margin. There is the possibility of water movement at the contact of the country rock and the dikes, accompanied by leaching of some chemical constituents, and margin samples were chosen to minimize this problem. Because of the discrete nature of the shearing, which was concentrated in the dikes, it was anticipated that any metasomatic changes within the wall rock would have occurred within a few centimeters of the margin.

Wall Rock Contamination in Mafic Terranes

As a final check, two Lower Proterozoic dikes were sampled at Lighthouse Point in Marquette (See Figure 4), where they intrude the meta-igneous Lighthouse Point Group (LHPG) rocks, (Gair and Thaden, 1968). Sampling of dikes intruding a mafic terrain permitted a chemical and structural comparison with the Republic dike samples. Qualitatively, wall rock contamination could be discounted as a major contributing mechanism responsible for the chemical trends of the marginal rocks if the LHP dikes displayed chemical trends similar to those of the Republic dike samples.

COMPARISON OF LIGHT VERSUS DARK MINERALS

A 1000 point count, comparing light (felsic) minerals and dark (mafic) minerals was performed on samples from several Republic area dikes. The procedure minimized the light/dark color bias inherent in petrography, providing a verification of conventional modal analyses. The results of the analyses are summarized in Table 1. In each dike, the margin or near-margin sample contains a greater percentage of dark minerals than the corresponding dike interior sample. This may be a result of alteration of minerals such as Ca-rich plagioclase, and removal of some constituents out of the system during deformation.

Table 1.--Comparison of light vs. dark minerals from samples of Republic area dikes 1, 3, and 4.

	Rep 1-1 Margin	Rep 1-3 Interior	Rep 3-1 Margin	Rep3-4 Interior	Rep 4-2 Near margin	Rep 4-4 Interior
Dark	82 %	78 %	79 %	73 %	83 %	80 %
Light	18 %	22 %	21 %	27 %	17 %	20 %

RESULTS OF LOSS ON IGNITION ANALYSIS

This procedure, which was modified from a procedure used by the Geology Division of the Research Council of Alberta, was used to determine the loss of H_2O, CO_2, CO_3, and other volatiles from rock samples.

It was necessary to account for ferrous iron, which is oxidized during the procedure. A typical diabase ferrous/ferric ratio of 1/3 is utilized for the calculations (Vogel, personal communication).

If fluid movement accompanied shearing along the dike margins, these samples should be more hydrous than dike interior samples, particularly where modal percentages of hydrous mafic minerals such as amphibole and mica increase toward the margins. This procedure provided a quantitative measure of those differences.

Samples from Republic area dikes 1, 3, and 4 were utilized for this procedure. A dike margin or near-margin sample and dike interior sample from each of the three dikes was prepared and analyzed.

The results of the analyses (Table 2) are inconclusive. In all dikes, the total modal percentage of mafic phases (biotite, amphibole, and chlorite) increases toward the margins. However, only dike 1 shows a large increase in bound water at the margin, 0.78%. Dike 3 follows, with a 0.14% increase, and unexpectedly, the results from dike 4 showed a decrease of 0.14% at the margin. The total amount of water in the samples varies from 1.23% (Republic dike 4) to 3.06% (Republic dike 1).

Procedure

Crucibles and crushed rock samples were heated to 50°C, under vacuum, to remove any non-bound water (crucibles for 1 hour, rock samples for 24 hours); then transferred to a desiccator and allowed to cool.

The crucibles were weighed and 1 gram of sample was added to each. The crucibles were transferred to a cool furnace, which was allowed to heat to 1100°C, with that temperature sustained for two hours. The crucibles were then removed to a desiccator and allowed to cool, and reweighed (all weights are +/- 0.0005 g).

Table 2.--Results of loss-on-ignition procedure for samples from Republic area dikes 1,3, and 4.

Sample	Location in dike	corrected loss on ignition (%)
Rep 1-1	Margin	2.28
Rep 1-3	Interior	3.06
Rep 3-1	Interior	2.24
Rep 3-4	Margin	2.10
Rep 4-2	Near margin	1.23
Rep 4-5	Interior	1.37

RESULTS OF PETROGRAPHIC ANALYSIS

The mineralogy, texture, amount of foliation, and composition of surrounding wall rock varies from dike to dike, and the Republic and LHP dikes are discussed individually in the following two sections.

Republic Dikes

The Republic dikes are comprised of amphibole (16-65%), plagioclase (5-35%), biotite (3-60%), quartz (0-12%), chlorite (0-20%), epidote/clinozoisite (0-8%), muscovite and other fine mica (0-10%), and lesser amounts of magnetite, ilmenite, hematite, sphene, and rutile.

Samples from the Republic dikes contain little evidence of the original igneous textures observed in samples from both LHP dikes. Recrystallization has replaced the diabase mineral assemblage of pyroxene and plagioclase, with an assemblage consisting primarily of amphibole, biotite, and plagioclase.

Pyroxene, which probably comprised much of the original diabase mineral assemblage, is absent in Republic dike samples. The initial alteration of pyroxene to amphibole is assumed to have been pseudomorphic, although the pseudomorphs are also absent.

Amphiboles in dike margin samples are typically needle-like, oriented sub-parallel to foliation, and non-poikiloblastic, while amphiboles in dike interior samples are commonly non-oriented, irregularly-shaped, and often poikiloblastic. Interior samples from several dikes contain amphiboles with bent cleavage traces and sweeping, radial extinction (Figure 7), indicative of grain-scale deformation, even in low-strain regimes. Amphiboles are frequently replaced by biotite or altering to chlorite (Figure 8). Amphiboles are pleochroic from green to blue-green.

Samples from highly-foliated dike margins commonly contain less amphibole and more fine-grained biotite (up to 60%), than samples with less-developed foliation. Bands of biotite in samples with less-developed foliation are typically deflected around coarser amphibole and plagioclase grains, while banding in samples with highly-developed foliation is more planar, with interstitial amphibole, plagioclase, and quartz. Biotite grains are pleochroic from pale yellow-brown to red.

Plagioclase grains in dike margin samples are typically non-twinned, non-sericitic, and interstitial, while grains in dike interior samples are more commonly twinned, highly sericitic, and in some cases may be remnants of original igneous texture (Figure 9). Alteration of plagioclase to

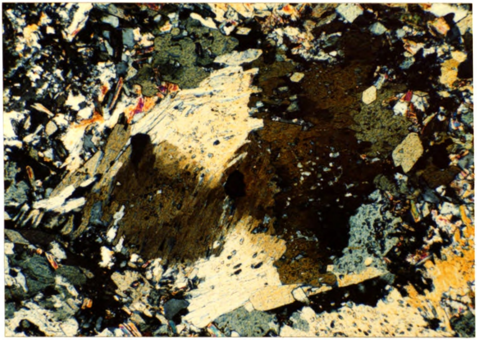


Figure 7.--Photomicrograph of amphibole from dike center sample, displaying curved cleavage traces, bent crystal boundaries, and radial extinction.

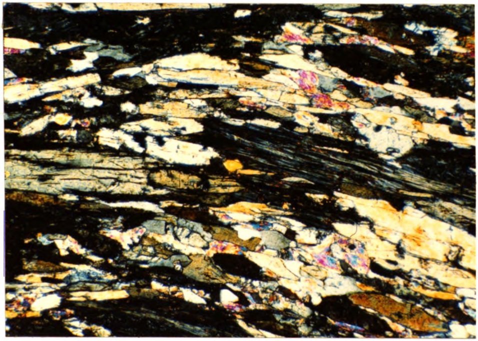


Figure 8.--Photomicrograph of amphibole from dike interior sample, showing alteration to chlorite and biotite.

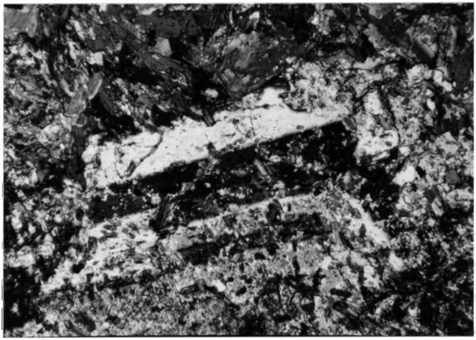


Figure 9.--Photomicrograph showing coarse, twinned, sericitic plagioclase, which may be a remnant of original igneous texture, dike center sample.

epidote/clinozoisite, muscovite, and sericite appears to have occurred initially along weaknesses in the crystal structure, such as twin-planes. In dikes 1-4, margin samples contain less plagioclase and plagioclase alteration products than corresponding interior samples. The condition of most twinned plagioclase grains precludes a statistically meaningful optical analysis of composition.

Quartz occurs as anhedral, interstitial grains, most commonly in margin samples. Granoblastic texture is observed where several quartz grains are in contact.

Wall Rock Petrographic Analysis

Two samples of wall rock intruded by each Republic area dike were analyzed. The wall rock was sampled at the dike margin and up to 9 m away from the dike margin. Foliation is visible at the outcrop scale, although no foliation is observed in thin section. Coarse grain size is probably responsible for this phenomenon.

The wall rock, which is similar for all five of the dikes, is comprised of plagioclase (35-45%), quartz (20-40%), K-feldspar (20-30%), biotite (trace-10%), muscovite (0-2%), chlorite (0-2%) and (0-1%) calcite, epidote, garnet, magnetite, rutile, sphene, and zircon. Grain size varies from fine to coarse, with most samples medium- to coarse-grained. The wall rock is classified a granitoid, using the IUGS Classification of Granites (Best, 1982).

Republic Dike 1

Dike Petrographic Analysis

Four samples of this dike were analyzed. The dike, which was approximately 1 m wide at outcrop, was sampled at the margin and 0.13 m, 0.27 m, and 0.5 m from margin.

The mineralogy and mode of this dike vary from interior to margin, with finer-grained, elongate amphiboles and coarser-grained biotite at the margin. Present in all samples are 2.5-3.0 mm clumps of subhedral-euhedral amphibole and biotite (Figure 10). Typically, these clumps are surrounded by much finer-grained minerals. These agglomerations probably formed when new amphibole and biotite crystals nucleated on older grains.

Modal analysis of the samples is summarized in Table 3. Modes of the two intermediate samples are combined. Most samples include fine, euhedral amphibole (0.05-0.15 mm), plagioclase, quartz, biotite, and sphene poikiloblastically enclosed within coarser amphiboles. Replacement of amphibole by biotite and chlorite is observed in all samples except the dike center sample. Sample Rep 1-3 contains amphiboles that appear to be altering to hematite, which may be the result of a weathering reaction. The dike center sample contains evidence of relict zoning within several amphiboles, which appears to be preserved from original

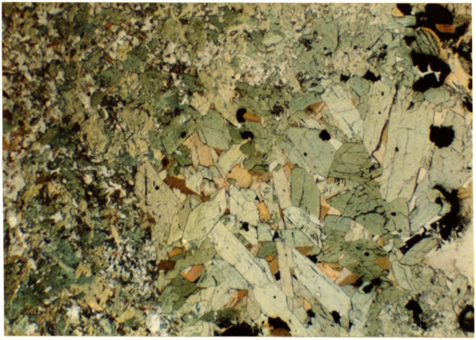


Figure 10.--Photomicrograph showing coarser, euhedral amphibole and biotite surrounded by fine-grained groundmass, dike center sample.

Table 3.--Modal analysis of Republic area dike 1.

	Sample 1-4 (center)			Sample 1-2 & 1-3 (interior)			Sample 1-1 (margin)		
Mineral	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape
amphibole	62	0.01-1.5	Anh-Euh	50	0.01-1.2	Anh-Euh	51	0.01-1.4	Anh-Euh
plagioclase	17	0.01-1.0	Anh-	12	0.01-1.0	Anh-	13	0.01-1.0	Anh-
biotite	15	0.01-0.25	Sub-Euh	25	0.01-0.4	Sub-Euh	30	0.01-0.5	Anh-Euh
quartz	5	0.01-0.1	Anh-	12	0.01-0.1	Anh-	5	0.01-0.1	Anh-
chlorite	none	-	Anh-Sub	trace	0.01-0.2	Anh-Sub	1	001-0.25	Anh-Sub
epidote/ clinozoisite	see note in text	-	-	see note in text	-	-	see note in text	-	-
muscovite	none	-	-	-	-	-	none	-	-
magnetite	trace	<0.01	Sub-Euh	none	-	-	none	-	-
ilmenite	trace	0.02	Anh-	none	-	-	none	-	-
hematite	trace	<0.01	???	trace	<0.01	???	none	-	-
sphene	1	0.01-0.08	Anh-Sub	1	0.01-0.05	Anh-Sub	trace	-	Anh-Sub
rutile	none	-	-	none	-	-	none	-	-

pyroxenes. Most plagioclase is sericitic and partially altered to epidote, and the two phases are difficult to separate. Most plagioclase grains in interior samples are twinned, although twinned grains are less prevalent in the margin sample. Broken and bent biotite grains are noted in all samples. Some biotite in the margin sample appears to be partially replaced by chlorite along the cleavage. Sample Rep 1-3 has ilmenite associated with sphene. Ilmenite may have been the source for titanium incorporated in the sphene (Barker, 1989), although this sample does contain more than one weight-percent TiO_2.

Republic Dike 2

Dike Petrographic Analysis

Two samples of this dike were analyzed. The dike, which was approximately 0.8 m wide at outcrop, was sampled at the margin and 0.4 m from the margin.

Grain size varies from interior to margin, with the margin sample being finer-grained. Foliation is well-developed in the dike margin sample, with bands of elongate amphibole, chlorite, and biotite. The fabric of the margin sample is deflected around a large clump of coarse plagioclase and this deflection appears to be associated with bending and breakage of biotites at grain contacts.

Many foliation-parallel zones are filled with very fine-grained sericite, which appear to be micro-shear zones.

Modal analysis of the samples is summarized in Table 4. Two varieties of amphibole are common, most prevalent are elongate prisms ranging in size from 0.05-0.25 mm, less common are coarser, irregularly-shaped grains with poikiloblastic texture. Plagioclase is typically non-twinned in both samples, and alteration to epidote is common. A modal decrease in epidote in the margin sample is accompanied by an increase in non-twinned plagioclase. Some biotite appears to be altering to hematite, which may be the result of a weathering reaction. Ten percent of each sample is comprised of very-fine mica in foliation-parallel mats, intergrown with coarser biotite and chlorite (Figure 11). Chlorite commonly has an anomalous-blue birefringence color.

Republic Dike 3

Dike Petrographic Analysis

Four samples of this dike were analyzed. The dike, which was approximately 4 m wide at outcrop, was sampled at the margin and 0.30 m, 0.66 m, and 2.02 m from the margin.

The dike was foliated, and it was anticipated that variations in mineralogy observed in the narrower dikes might also be observed in this dike.

Table 4.--Modal analysis of Republic area dike 2.

Mineral	Sample 2-2 (center) Mode (%)	Grain size (mm)	Grain shape	Sample 2-1 (margin) Mode (%)	Grain size (mm)	Grain shape
amphibole	54	0.01-1.0	Anh-Euh	50	0.01-1.0	Anh-Euh
plagioclase	11	0.05-0.75	Anh-Sub	14	0.01-10	Anh-Sub
biotite	10	0.01-0.75	Sub-Euh	3	0.01-0.75	Sub-Euh
quartz	none	-	-	1	-	-
chlorite	7	<0.01-0.03	?- Sub	20	<0.01-0.15	?- Sub
epidote / clinozoisite	8	0.01-0.1	Anh-	2	0.01-0.1	Anh-
muscovite/ misc. fine mica	10	<0.01-0.03	?- Sub	10	<0.01-0.03-	?- Sub
magnetite	trace	<0.01	???	none	-	-
ilmenite	none	-	-	none	-	-
hematite	trace	<0.01	???	none	-	-
sphene	none	-	-	trace	<0.01	???
rutile	none	-	-	none	-	-

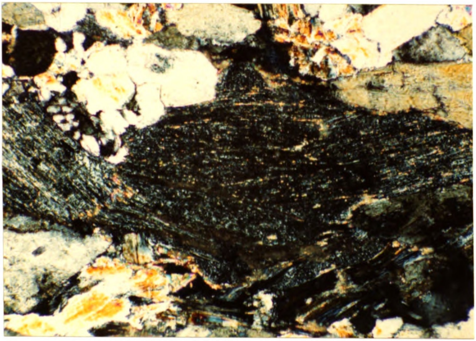


Figure 11.--Photomicrograph of elongate fibrous mat of very fine mica, and coarser chlorite and biotite, dike center sample.

The mineralogy of this dike varies considerably from interior to margin. Highly-foliated, fine-grained biotite dominates the mineral suite at the margin, while medium- to coarse-grained, irregularly-shaped amphibole is dominant in interior samples.

Modal analysis of the samples is summarized in Table 5. Interior samples contain coarse poikiloblastic amphiboles enclosing finer euhedral amphibole (0.1-0.15 mm), biotite, plagioclase, quartz, and magnetite. Some amphiboles appear to be altering (some pseudomorphic) to biotite, chlorite, and magnetite. Plagioclase is commonly twinned in interior samples, and non-twinned in the margin sample. Sericitization is most widespread in sample Rep 3-2, but is noted in all samples. Some alteration of plagioclase to epidote occurs in interior samples. Fabric in the margin sample is notable, with elongate, biotites displaying well-developed primary foliation and superimposed crenulation-cleavage (Figure 12).

<u>Republic Dike 4</u>

Dike Petrographic Analysis

Five samples of this dike were analyzed. The dike, which was approximately 1 m wide at outcrop, was sampled at the margin and 0.15 m, 0.3 m, and 0.5 m from the margin.

Table 5.--Modal analysis of Republic area dike 3.

	Sample 3-3 (center)			Sample 3-2 (interior)			Sample 3-1 (margin)		
Mineral	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape
amphibole	46	0.05-5.0	Anh-Euh	50	0.01-5.0	Anh-Euh	16	0.01-1.0	Anh-Suh
plagioclase	25	0.04-1.5	Sub-Euh	35	0.01-1.0	Anh-Sub	20	0.01-0.5	Anh-Sub
biotite	21	0.01-0.5	Sub-Euh	3	0.01-0.1	Sub-Euh	60	0.01-0.5	Anh-Euh
quartz	none	-	-	none	-	-	3	0.01-0.3	Anh-Sub
chlorite	5	0.01-0.1	Anh-Euh	5	0.01-0.2	Anh-Sub	none		
epidote/ clinozoisite	1	0.01-0.05	Anh-Sub	trace	0.01-0.05	Anh-Sub	trace	Anh-Sub	0.01-0.5
muscovite	none	-	-	none	-	-	none	-	-
magnetite	1	0.01-0.1	Anh-Sub	5	0.01-0..15	Anh-Euh	1	0.01-0.25	Anh-Sub
ilmenite	none	-	-	none	-	-	none	-	-
hematite	none	-	-	none	-	-	none	-	-
sphene	none	-	-	none	-	-	none	-	-
rutile	none	-	-	none	-	-	none	-	-

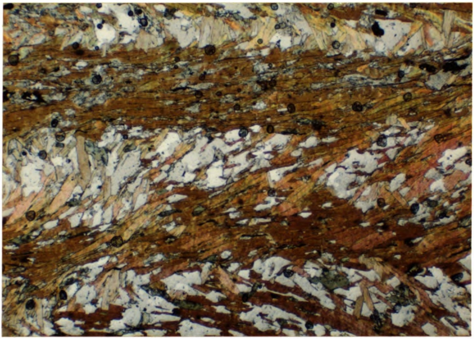


Figure 12.--Photomicrograph of fabric in dike margin sample, euhedral biotites displaying primary foliation (horizontal) and superimposed crenulation cleavage (semi-vertical, sigmoidal bands).

This dike appeared to be have well-developed foliation in outcrop, but petrographic examination of oriented thin-sections disclosed foliation that was less-pervasive than that of other Republic dikes. Even at the margin, shear strain appears to have been low enough that fabric development was limited to bands of biotite that appear to be deflected by coarser grains. These observations are more typical of those noted for dike interior samples from other Republic dikes.

A modal analysis representative of the samples is summarized in Table 6. Poikiloblastic amphiboles enclose fine euhedral amphibole (0.05-0.75 mm), quartz, plagioclase, and biotite. Plagioclase is commonly twinned in interior samples, while twinned and non-twinned grains occur in the margin sample. In all samples, some plagioclase is sericitic, and alteration to epidote is noted. Sphene in sample Rep 4-4 appears to be an alteration or replacement of magnetite or ilmenite (Barker, 1989). Chlorite is found in sample Rep 4-3, with anomalous-blue birefringence.

Republic Dike 5

Dike Petrographic Analysis

Two samples of this dike were analyzed. The dike, which was approximately 0.25-0.33 m wide at outcrop, was sampled at the margin and 0.15 m from the margin.

Table 6.--Modal analysis of Republic area dike 4.

	Sample 4-5 (center)			Sample 4-3 (interior)			Sample 4-1 (margin)		
Mineral	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape
amphibole	65	0.05-3.5	Anh-Euh	62	0.01-2.5	Anh-Euh	46	0.05-1.5	Anh-Sub
plagioclase	21	0.01-0.75	Anh-Sub	25	0.01-0.8	Anh-Sub	15	0.05-0.6	Anh-
biotite	12	0.01-0.2	Sub-Euh	14	0.01-0.1	Sub-Euh	36	0.01-1.0	Sub-Euh
quartz	none	-	-	none	-	-	3	0.01-0.5	Anh
chlorite	none	-	-	trace-1	0.05-0.15	Sub-	none		
epidote / clinozoisite	trace	<0.01	???	none	-	-	trace	<0.01-0.08	Anh
muscovite	none	-	-	none	-	-	none	-	-
magnetite	trace	<0.01	???	trace	<0.01	???	none	-	-
ilmenite	none	-	-	none	-	-	none	-	-
hematite	none	-	-	none	-	-	none	-	-
sphene	trace-1	<0.01	???	trace	0.01-0.05	Sub-	none	-	-
rutile	none	-	-	none	-	-	none	-	-

The dike was foliated, and it was anticipated that variations in mineralogy observed in wider dikes might also be observed in this dike.

Grain size varies from interior to margin, with the margin sample being finer-grained. The margin sample has well-developed foliation, although the presence of medium (<3.0 mm), non-oriented amphiboles appears to have influenced the parallel alignment of biotites.

Modal analysis of the samples is summarized in Table 7. Irregularly-shaped poikiloblastic amphiboles enclose biotite, sphene, quartz, and plagioclase, and are most prevalent in the margin sample. Twinned and non-twinned interstitial plagioclase grains are common in both samples. Plagioclase is partially altered to highly-birefringent epidote. Unlike the other Republic dikes, a modal increase in plagioclase is noted in the margin sample, and the appearance of plagioclase in the margin sample is more typical of grains observed in interior samples in other dikes.

Lighthouse Point Dikes

The Lighthouse Point dikes are comprised of amphibole (15-35%), chlorite (15-35%), plagioclase (5-40%), relict pyroxene (0-20%), quartz (0-40%), calcite (0-12%), epidote/clinozoisite (trace-12%), biotite (0-5%), and minor amounts (<5%) of opaques, and rutile.

Table 7.--Modal analysis of Republic area dike 5.

	Sample 5-2 (center)			Sample 5-1 (margin)		
Mineral	Mode (%)	Grain size (mm)	Grain shape	Mode (%)	Grain size (mm)	Grain shape
amphibole	50	0.01-3.0	Anh-	55	Anh-	0.25-3.0
plagioclase	11	0.03-0.05	Anh-Sub	5	0.03-0.4	Anh-Euh
biotite	30	0.01-0.5	Sub-Euh	30	0.01-0.75	Sub-Euh
quartz	none			2	0.01-0.1	Anh
chlorite	9	0.01-0.4	Anh-Euh	5	0.01-0.3	Anh-Sub
epidote / clinozoisite	none	-	-	1	0.01-0.05	Sub
muscovite	none	-	-	none	-	-
magnetite	none	-	-	trace	<0.01-0.05	Euh
ilmenite	none	-	-	none	-	-
hematite	none	-	-	none	-	-
sphene	1	<0.03	Anh-Euh	trace	<0.05	Euh
rutile	none	-	-	none	-	-

The LHP dikes trend approximately east-west and north-south, with near-vertical dips. These trends are orthogonal to the Penokean-age maximum principle stress direction of 03/192 (Myers, 1984). Although neither sampled dike was foliated, proximity to the north limb of the Marquette Trough indicates that these dikes were exposed to considerable stress during the Penokean Orogeny. Despite the lack of shearing, the samples are highly metamorphosed, and pyroxene is partially to completely replaced by amphibole and opaques.

The wall rock surrounding the LHP dikes is a layered amphibole schist interpreted by Gair and Thaden (1968) as primarily metavolcanics, comprised of amphibole, plagioclase, quartz, chlorite, biotite, and opaque minerals (which typically appear to be psuedomorphs of pyroxene).

East-West Dike

Dike Petrographic Analysis

An interior and margin sample of this dike and an interior sample from the wall rock were analyzed. Wall rock at the margin was heavily weathered and it was determined that sampling might reflect weathered mineral assemblages. No preferred mineral orientation was noted in any samples.

Modal analysis of the samples is summarized in Table 8. Coarser plagioclase grains are typically elongate, while

Table 8.--Modal analysis of Lighthouse Point east-west dike.

Mineral	Sample LHP E-W (center) Mode (%)	Grain size (mm)	Grain shape	Sample LHP E-W (margin) Mode (%)	Grain size (mm)	Grain shape
amphibole	15	0.01-1.5	Sub-Euh	25	0.01-1.2	Anh-
plagioclase	35	0.1-5.0	Anh-Sub	35	0.1-3.0	Anh-Sub
pyroxene	20	0.01-1.0	Anh-Sub	12	0.01-1.0	Anh-
K-feldspar	none	-	-	5	0.01.-1.5	Anh
quartz	5	0.01-0.5	Anh	none	-	-
chlorite	15	0.1-1.0	Anh-Sub	15	0.1-1.0	Anh-Euh
epidote / clinozoisite	none	-	-	1+	<0.05	Anh
magnetite	10	<0.1	Anh-Sub-	5	<0.1	Anh-
hematite	2	<0.01	???	none	<0.01	???
calcite	none	-	-	trace	<0.1	Sub-Euh
rutile	trace	<0.01	???	none	<0.01	???

finer grains (<0.5 mm) are more equant. Twinned and sericitic grains are typical in both samples, although sericitized grains are more common in the interior sample. Twin-plane controlled dissolution is noted in grains from the margin sample. Poikiloblastic plagioclase grains enclose fine amphibole, chlorite, and opaque minerals. Zoned plagioclase grains occur in the dike interior sample. Many amphiboles in the margin sample appear to be altering to chlorite, and several amphiboles with bent cleavage traces and sweeping extinction similar to Figure 7 are noted. Amphiboles are pleochroic from green to blue-green to brown. Most pyroxenes appear to be altering (some pseudomorphic) to magnetite, chlorite, and amphibole. Typically, grain interiors are comprised of birefringent pyroxene, surrounded by a reaction rim of opaque minerals and amphibole (Figure 13). Several relict pyroxenes display sweeping extinction. Pyroxenes are pleochroic from brown-green to brown, suggesting that most grains are augite (Philpotts, 1989). Myrmekitic intergrowths of quartz and feldspar are observed in the dike interior sample. The interior sample contains trace amounts of rutile (needles in quartz grains), and calcite and epidote/clinozoisite (singular grains and fracture fill). The presence of calcite and epidote/clinozoisite is consistent with the breakdown of Ca-plagioclase (Philpotts, 1989), although no modal decrease at the margin is noted.

Figure 13.--Photomicrograph of altered pyroxene, with significant alteration to opaque minerals. Surrounding grains display remnant igneous textures.

North-South Dike

Dike Petrographic Analysis

An interior and a margin sample of this dike, and the surrounding wall rock were analyzed.

Mode, grain size (the margin sample is primarily fine-grained), and metamorphism and replacement of minerals varies from interior to margin in this dike. Although some coarse-grained igneous texture is observed, most has been replaced by a much finer-grained mineral suite. Absent from this dike are the relict pyroxenes and opaque minerals common in the east-west trending LHP dike. No preferred mineral orientation was noted in any samples.

Modal analysis of the samples is summarized in Table 9. Plagioclase grains are commonly twinned and heavily sericitic, with twin-plane controlled dissolution, and epidote/clinozoisite filled cavities. Several grains poikiloblastically enclose fine quartz and biotite. There is some alteration of amphibole to chlorite in the interior sample, with some complete replacement in the margin sample. Amphiboles are pleochroic from green to blue-green. Quartz occurs as inclusions in the interior sample, and interstitial grains in the margin sample. The fine grain size precludes an optical determination of many suspected quartz grains and the mode reflects the inclusion of these

Table 9.--Modal analysis of Lighthouse Point north-south dike.

Mineral	Sample LHP N-S (center) Mode (%)	Grain size (mm)	Grain shape	Sample LHP N-S (margin) Mode (%)	Grain size (mm)	Grain shape
amphibole	35	0.1-1.0	Sub-Euh	5	0.1-1.0	Anh-Sub
plagioclase	35	0.1-2.5	Anh-Sub	25	0.1-2.5	Anh-Sub
pyroxene	none	-	-	none	-	-
biotite	5	0.1-1.0	Sub-Euh	5+	0.1-1.0	
quartz	5	<0.1	Anh-Sub	20	<0.1	Anh
chlorite	8	0.1-0.7	Sub-Euh	25	0.01-0.07	Anh-Sub-
epidote / clinozoisite	12	<0.05	Anh-	5	<0.05	Anh-Sub
magnetite	none	-	-	none	-	-
calcite	none	-	-	12	0.1-0.3	Sub-Euh
rutile	none	-	-	trace	<0.01-	???

unknowns, which may actually be feldspar. Biotite is pleochroic from yellow-brown to red.

The presence of calcite and decrease in modal plagioclase and epidote/clinozoisite in the margin sample is consistent with breakdown of Ca-plagioclase (Philpotts, 1989) and removal of calcium from the system. Although this dike was not sheared, the mineralogy of the interior and margin samples are markedly different.

ANALYSIS OF SHEAR STRAIN

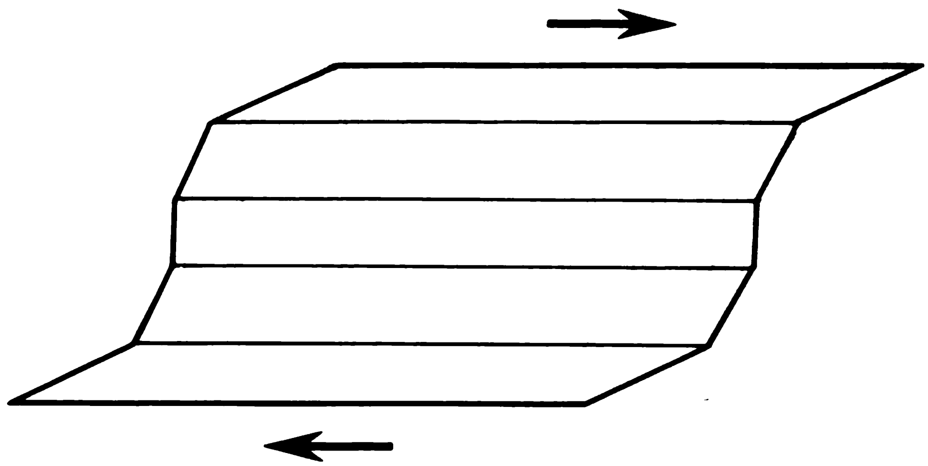
Crystalline basement terranes deformed under metamorphic conditions frequently contain localized, narrow, and sub-parallel shear zones. Although brittle and combination brittle-ductile shear zones are common at higher crustal levels, ductile shear zones may be their deep-level counterparts. Ductile shear zones appear to be the dominant deformation mode at depth, under medium to high grades of deformation (Ramsay, 1980). The foliated Lower Proterozoic dikes near the Republic Trough are thought to have been deformed and displaced as a result of ductile flow (Myers, 1984). Although Myers and others have studied the bulk-strain analyses of these dikes, this section will characterize the shear strain of individual Republic area dikes.

Ramsay (1980) suggests that the basic component in nearly all shear zones is heterogeneous simple shear. He also suggests that unstrained walls in a shear zone indicate that volume change may have accompanied the shearing. The variation in intensity of foliation and changes in mineralogy from dike center to dike margin is an indication of increasing shear strain over that interval and is interpreted as the result of heterogeneous simple shear.

The dike margins of the Republic area dikes appear largely unstrained, as evidenced by the linear contacts and lack of dike margin-parallel foliation within the wall rock. These features indicate that the wall rocks remained largely rigid, while the dikes deformed as a result of heterogeneous simple shear during deformation.

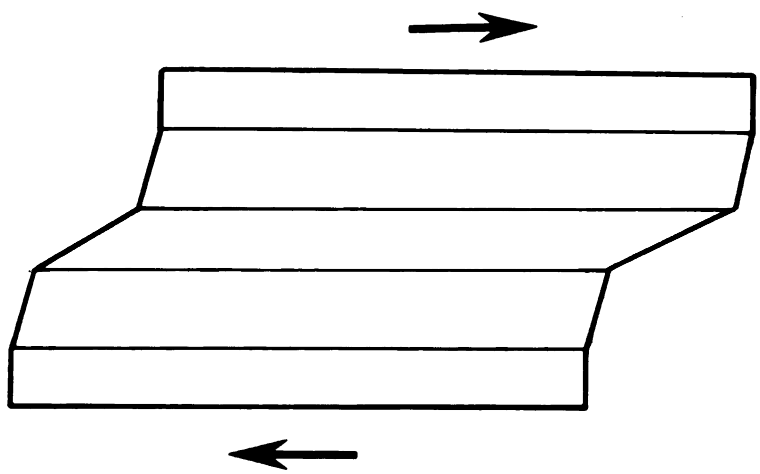
The Republic area dikes have a single low-strain zone running down the approximate center of the dikes, and two high-strain zones sub-parallel and immediately adjacent to the dike margins (Figure 14a), while classic shear zones typically contain two low-strain zones along the margins and a single high-strain zone in the approximate center of the shear zone (Figure 14b). These differences are probably the result of shearing that was concentrated in discrete mafic bodies (diabase dikes) intruded into felsic country rocks, while most classical shear-zone studies have examined shear zones in either felsic <u>or</u> mafic rocks. A deformed rectangular shape is shown in each figure. The line of maximum extension is increasingly parallel to margins of the shear zone in Figure 14a and the center of the shear zone in Figure 14b.

The geometry and methods of analyzing shear zones is well documented by Ramsay (1967); Ramsay and Graham (1970); Ramsay (1980); and Ramsay and Huber (1983), and the methods used to analyze the Republic area dikes are largely excerpted from these previous studies. Two boundary



Indicates shearing direction

Figure 14a.--Diagram illustrating the geometry of a typical shear zone in heterogeneous rocks.



Indicates shearing direction

Figure 14b.--Diagram illustrating the geometry of a typical shear zone in homogeneous rocks.

conditions and several assumptions are necessary to analyze the sheared Republic area dikes as heterogeneous simple shear zones. Ramsay (1980) suggests that although boundary conditions are never completely realistic, most shear zones approximate these boundary conditions.

Boundary conditions:

a) shear zone is parallel-sided

b) displacement profiles along any cross-section of the zone are identical

Assumptions:

a) although the shear zone is heterogeneous, small enough pieces (infinitesimally small) can be analyzed such that each piece is behaving as a homogeneous simple shear

b) only the shearing component of the stress vector is considered, the flattening component is ignored or assumed to be minimal, or cannot be determined

c) volume loss is negated for this portion of the study, if there was volume loss, it will be considered separately, although the two events may have occurred simultaneously

d) the entire shear zone is isotropic

Figure 15 summarizes the relation of the strain ellipse to shear in the simple shear system. In this system, a cube (a) is displaced by opposing horizontal shear forces, resulting in a trapezoidal shape (b), where X_f is the line of maximum extension, Z_f is the line of minimum extension, and $Y_f=1$ (no extension). The mathematical relations are:

$$\gamma = \tan\varphi$$
$$\gamma = {}^{2}/\tan\theta'$$

where φ is angular shear strain, θ' is the angle measured from the shear zone margin to the line of maximum extension (foliation), and γ is shear strain.

The sigmoidal line of foliation (line of maximum extension) was well developed in three of the Republic area dikes; 1, 2, and 5. The foliation in dike 2 was preserved through the width of the dike, and the analysis reflects the total shear strain for that dike. Dike 1 had foliation that was poorly preserved at one margin, while a portion of wall rock/dike margin was missing at dike 5, consequently the shear strain measurements apply only for the measured portion of these dikes. The results of shear strain analyses is summarized in Table 10.

Table 10.--Comparison of shear strain values for Republic area dikes 1, 2, and 5. Angle θ' is the angle measured from dike margin to line of maximum extension (foliation).

	Distance across shear zone, from dike margin (m)	Distance across shear zone, from dike margin (%)	θ' (degrees)	2θ' (degrees)	$\gamma = {}^2/_{\tan 2\theta'}$ (gamma units)
Dike 1	0.03	2	5	10	11.34
	0.15	12	15	30	3.46
	0.30	25	45	90	0.0
	0.61	50	55	110	-0.73
Dike 2	0.03	4	5	10	11.34
	0.08	11	15	30	3.46
	0.15	22	38	76	0.50
	0.35	50	53	106	-0.57
	0.55	78	33	66	0.89
	0.68	96	5	10	11.34
Dike 5	0.05	10	5	10	11.34
	0.04	30	17	34	2.97
	0.08	60	32	64	0.98

As shear displacement gets large, θ' becomes small, culminating in the formation of foliation, schistosity, and cleavage. Ramsay (1980) cautions that measurement errors for small θ' can lead to very large errors during computation of total shear zone displacement. In the dikes 1, 2, and 5, the foliation is nearly asymptotic at the dike margins and measurements of θ' smaller than 5° were not attempted.

To calculate total displacement across the shear zone, shear strain is plotted as a function of distance across the shear zone:

$$s = \int_{o}^{x} \gamma dx$$

where s is total displacement. Several graphical methods for solving this equation are outlined in Ramsay and Huber (1983), or the integral may be solved using Simpson's rule. Ramsay and Huber (1983) show that the results of all the methods are quite similar. A graphical approximation of the area under the strain/distance curve was derived for this analysis using an electronic planimeter (Figure 16). The total displacements for the three dikes are presented in the form of gamma units (γ).

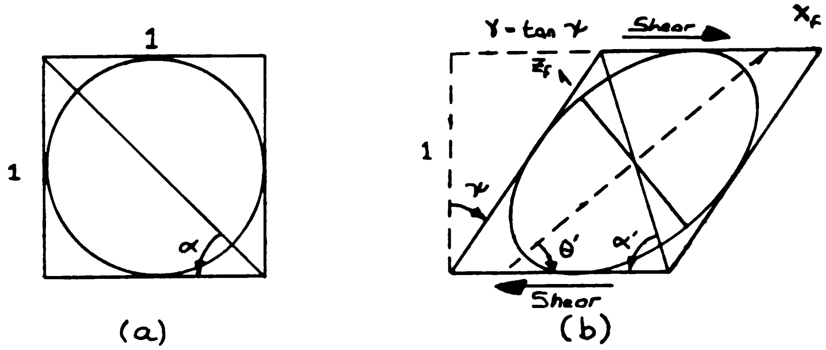


Figure 15.--Diagram illustrating the relation of the strain ellipse to shear in the simple shear system.

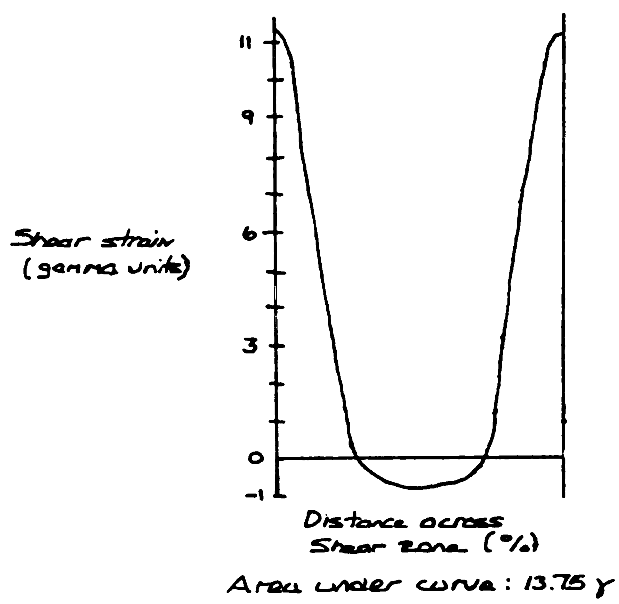


Figure 16.--Diagram illustrating a graphical approximation of total displacement (γ units) for dike 2 by finding the area under the strain/distance curve.

The measurements for dikes 1 and 5 are incomplete because of previously mentioned difficulties.

Republic dike 1: 10.9 γ

Republic dike 2: 13.8 γ

Republic dike 5: 4.6 γ

Given a margin of measurement error of ±5° , if θ' at the dike margin was actually 10°, instead of 5°, γ would be $\cong$ 5.5 and total displacement would be several γ units less, but still significant. A θ' measurement of 0°, which represents foliation parallel to the shear zone, results in infinite shear strain and total displacement (due to the limitations of the trigonometric functions).

The total displacement values can be used to calculate the principal strains in the x_f (maximum extension) and z_f (minimum extension) directions by using the following equation from Ramsay (1967):

$$(1 + e_1)^2 \text{ or } (1 + e_3)^2 = (\gamma^2 + 2 \pm \gamma(\gamma^2 + 4)^{\frac{1}{2}})/2$$

where the principal strain in the x_f direction is $(1 + e_1)^2$, and the principal strain in the z_f direction is $(1 + e_3)^2$. The principal strains for the three Republic area dikes are presented below, where the original unstrained value for each of the principal strains is 1.0.

Republic dike 1 $(1 + e_1)^2 = 11.0$

$(1 + e_3)^2 = 0.1$

Republic dike 2 $(1 + e_1)^2 = 13.9$

$(1 + e_3)^2 = 0.07$

Republic dike 5 $(1 + e_1)^2 = 5.0$

$(1 + e_3)^2 = 0.2$

These values are significant, indicating that extension along the x_f direction in Republic dike 2 was nearly 13.9 times the original, unstrained length, while the length of the z_f is 0.07 times the original, unstrained length. The strain values of x_f are high, but similar to strains measured in slate belts (Wood, 1974).

Quantitative calculation of volume loss is impossible using this data set. The methods outlined in Ramsay (1980) depend on the availability of one or more strain markers, such as a displaced, cross-cutting mineral vein. Likewise, the lack of strain markers precludes application of Gresen's equations (1967).

RESULTS OF X-RAY FLUORESCENCE ANALYSIS

XRF analysis provides a means of determining if appreciable volume loss may have occurred during deformation. In rocks lacking useable strain indicators, bulk-rock chemical analysis is the only means of determining volume change. A comparison of bulk-rock chemistry for samples from low- and high-strain regimes, allows inferences to be made regarding the role of volume loss.

Major oxide and trace element analyses are compiled in appendices 1-5, which contain data for Republic dikes 1-5, and appendices 6 and 7, which contain data for Lighthouse Point dikes trending east-west and north-south, respectively. The major oxide data is listed in weight percent and trace element data is listed in parts per million.

Recent studies of volume loss in high-strain regimes have noted significant depletion of SiO_2, CaO, and other mobile elements, and enrichment of conserved trace elements (O'Hara, 1990; Glazner and Bartley, 1991). These studies examined quartz-rich rocks with significantly higher silica content than the dikes of this study. Although significant depletion of calcium is noted in the high-strain regimes of several dikes, substantial silica depletion and many-fold enrichments in immobile trace elements (used as primary evidence for significant volume loss in other studies) are conspicuously absent. Solution transfer removal of materials from these dikes was probably influenced by the lack of free quartz.

Petrographic analysis has shown that the textures and mineralogy of the dikes differ from low-strain regime to high-strain regime. If volume loss occurred as a result of Ca-rich plagioclase dissolution, as the petrographic observations seem to indicate, calcium depletion should accompany increasing strain. If volume loss accompanied shearing, the trends in bulk-rock chemistry for the sheared Republic area dikes and the non-sheared Lighthouse Point dikes could also be quite different.

The following section is intended as a brief review of the data. The discussion will refer to a particular oxide or element at the dike margin, in comparison with that oxide or element in the dike interior, unless otherwise noted. For illustrative purposes, bulk-rock data is plotted against sampling distance from the dike margin in figures throughout this section allowing comparison of the behavior of a particular element or oxides in various strain regimes. The Republic and LHP dikes are plotted on separate diagrams.

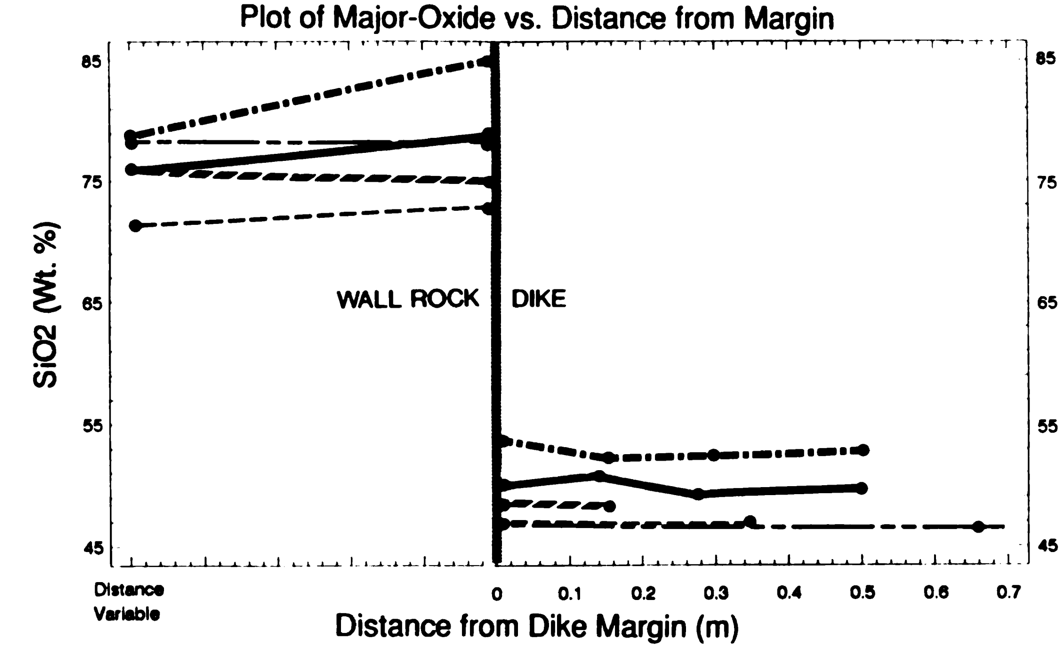
Major Oxides

SiO_2 was unexpectedly stable. The trend of SiO_2 for the Republic dikes is nearly flat, with less than one weight-percent change in concentrations (Figure 17a). The LHP dikes show trends of less than 1.5 weight-percent change in concentration (Figure 17b). Lack of quartz may in part explain these trends.

Al_2O_3 is depleted toward the dike margin in all Republic dikes (Figure 18a). Although the depletions are less than one weight percent, it is significant that trends are similar for all dikes, in an oxide that is typically considered to be conserved. The LHP dikes had opposing trends (Figure 18b), with variation of less than one percent. Al_2O_3 variation in the wall rock surrounding several of the dikes is much greater than the variation in the corresponding dikes.

Republic dikes 2 and 3, and both LHP dikes show enrichments in FeO, which is Fe_{total}, at the dike margins, which contrasts with flat trends in other Republic dikes (Figures 19a,b). Enrichment in FeO could be interpreted as a relative gain in these dikes due to a loss of other elements (constant sum effect).

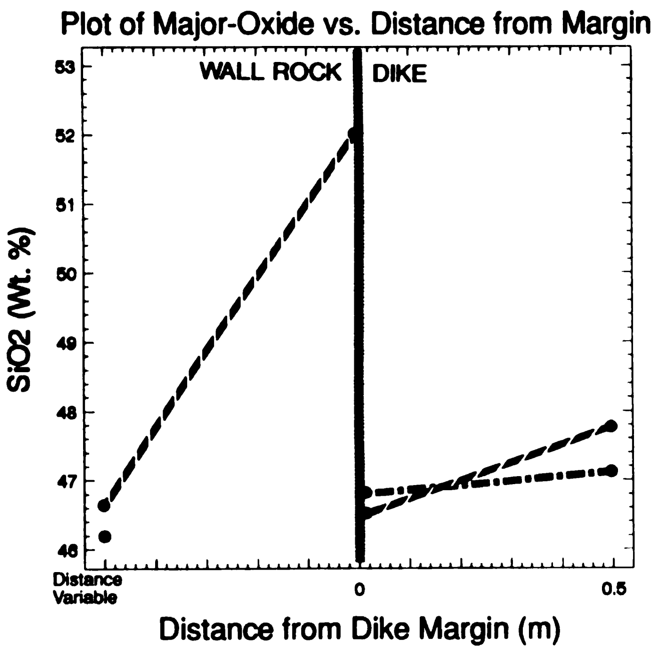
Republic dikes 3 and 4 show enrichments in MgO, at the dike margins, of as much as two weight-percent, contrasting with nearly flat to slightly changing trends in other Republic dikes, and LHP dikes (Figures 20a,b). Enrichment



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

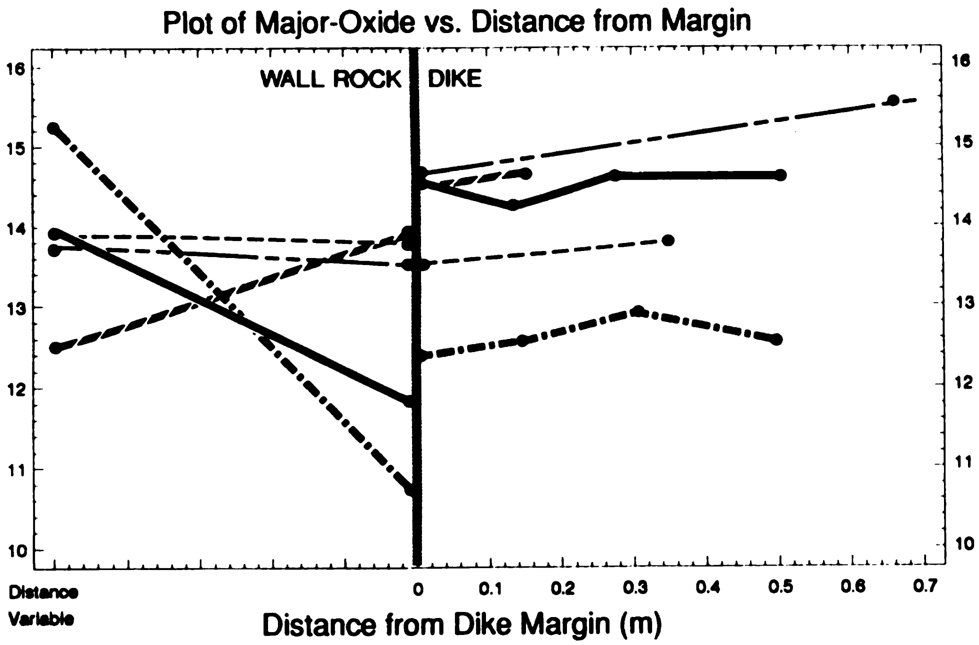
Figure 17a.--Plot of SiO_2 vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

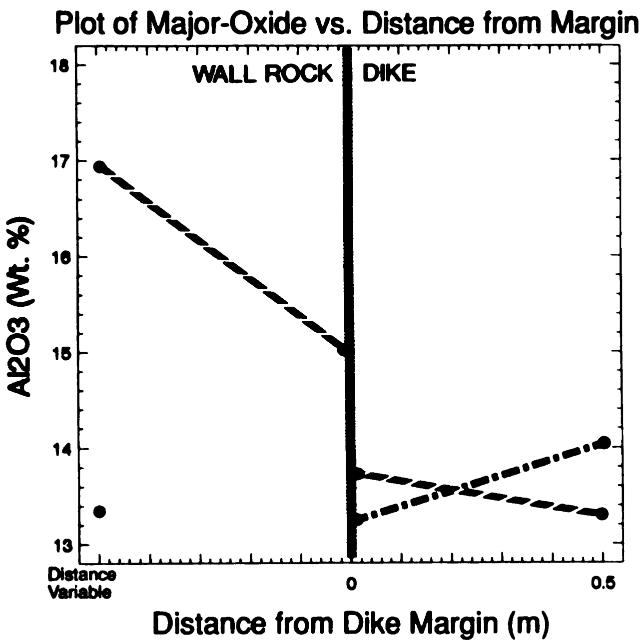
Figure 17b.--Plot of SiO_2 vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

Figure 18a.--Plot of Al_2O_3 vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

Figure 18b.--Plot of Al_2O_3 vs. distance from dike margin for Lighthouse Point dikes.

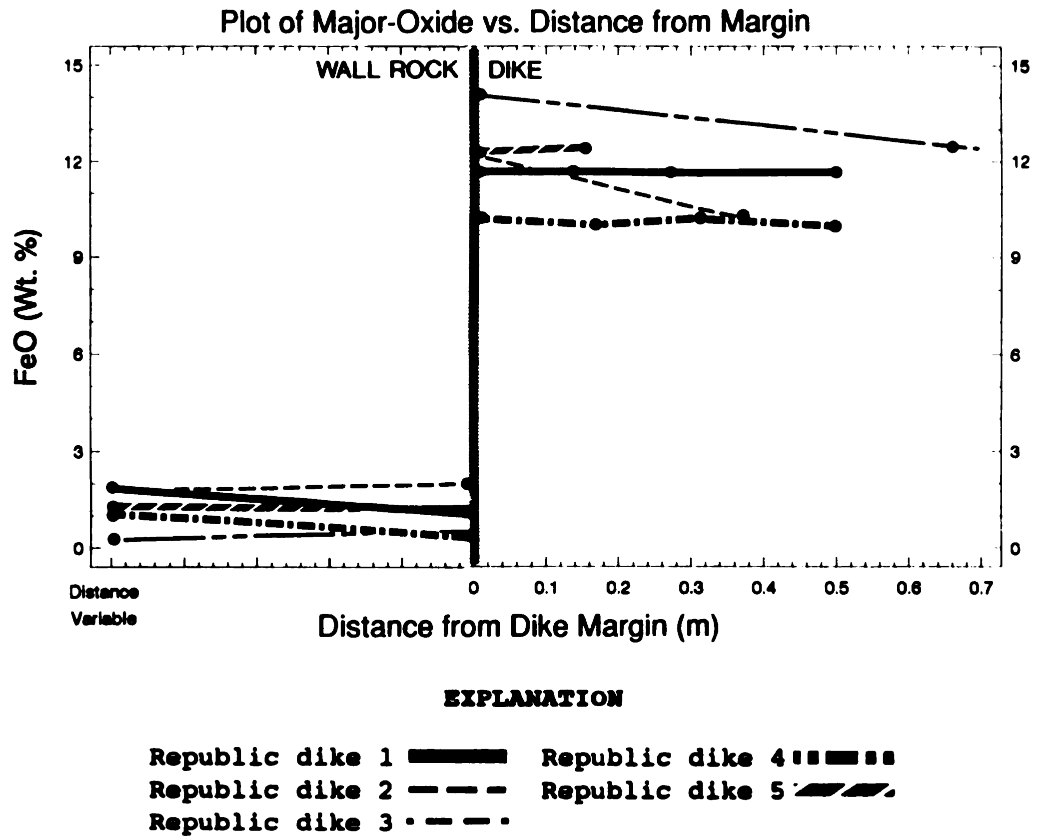


Figure 19a.--Plot of FeO vs. distance from dike margin for Republic area dikes.

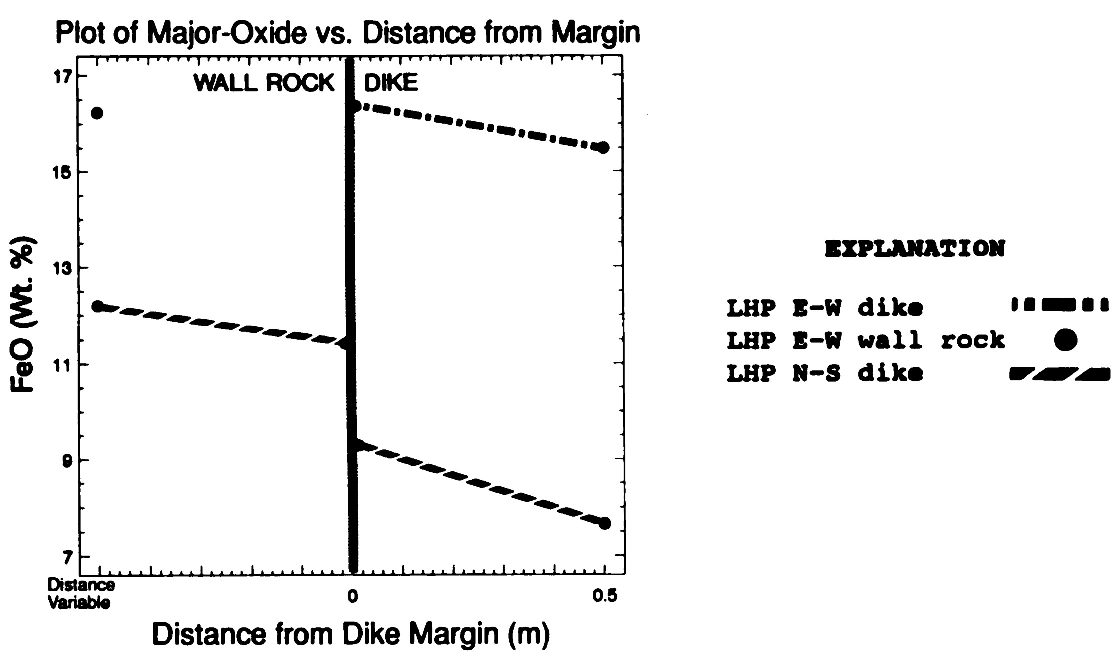
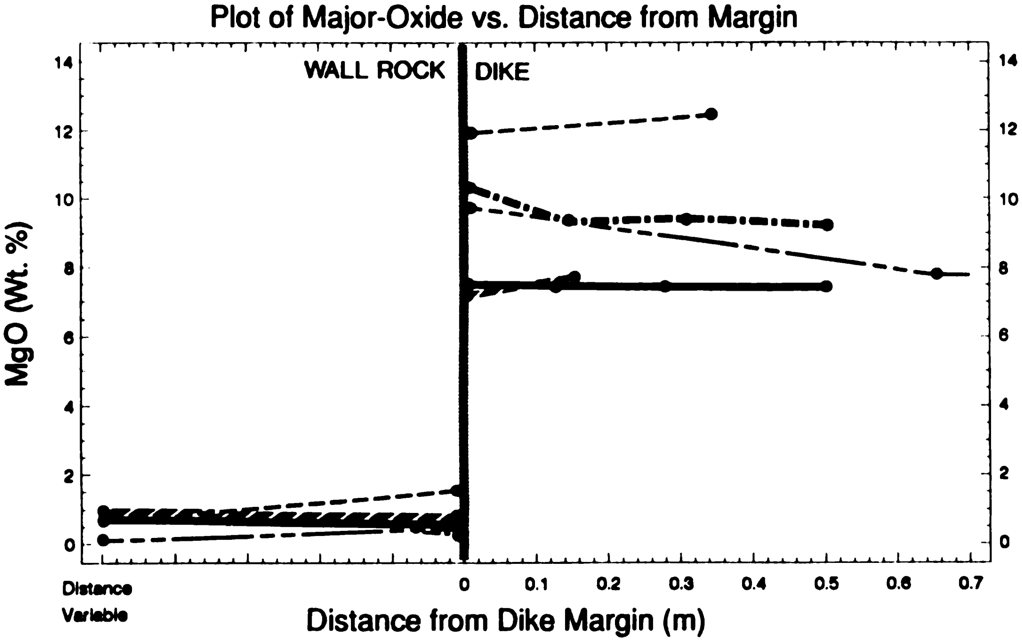


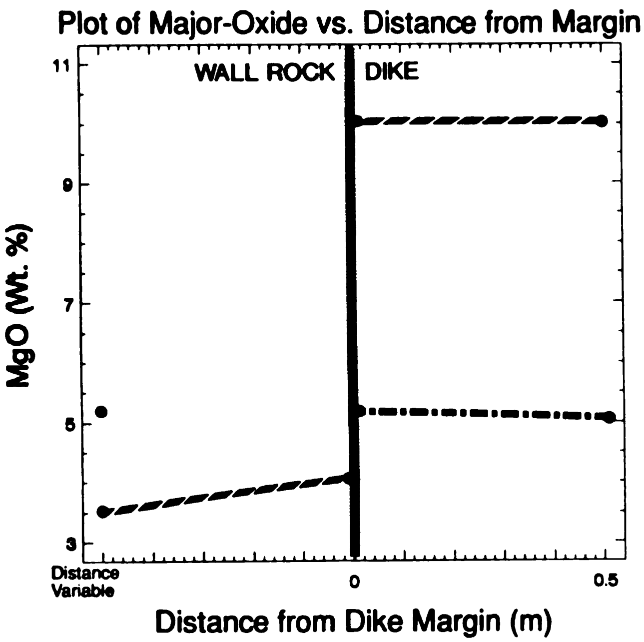
Figure 19b.--Plot of FeO vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

Figure 20a.--Plot of MgO vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

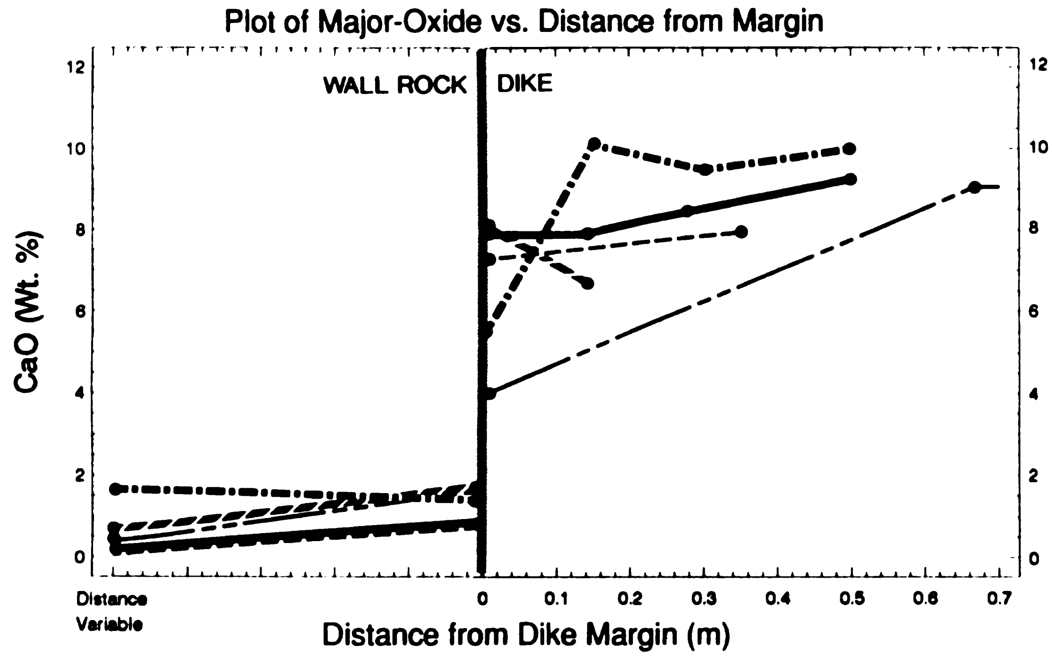
Figure 20b.--Plot of MgO vs. distance from dike margin for Lighthouse Point dikes.

in MgO could also be interpreted as a relative gain in dikes 3 and 4 due to a loss of other element(s).

As anticipated, the Republic dikes, except dike 5, show depletions in CaO at the dike margins (Figure 21a). Although CaO in dike 5 was enriched approximately two weight percent at the margin, a modal decrease in plagioclase was noted at the margin. The depletions of CaO represent the largest changes of a major oxide noted in these samples, approximately 50 percent of the total CaO for Republic dikes 3 and 4. The trends of the LHP dikes oppose one another with a change of approximately one weight-percent (Figure 21b). The depletion of CaO toward the margins of the Republic dikes parallels petrographic observations of decreased modal amounts of plagioclase and plagioclase alteration products in some margin samples. Variation in CaO is much greater in the wall rock surrounding the north-south trending LHP dike, than in the dike itself.

Republic dikes 2, 3 and 4, and both LHP dikes show depletions of Na_2O ranging from 0.1 to 0.5 weight percent Na_2O, at the dike margins (Figures 22a,b). Na_2O trends are nearly flat for Republic dikes 1 and 2, while dike 5 is enriched at the margin. Na_2O and CaO trends of dikes 2, 3, 4, and 5 are similar, and may be evidence of volume change in these dikes. Variation in Na_2O is much greater in the wall rock of several Republic dikes, than in the dikes.

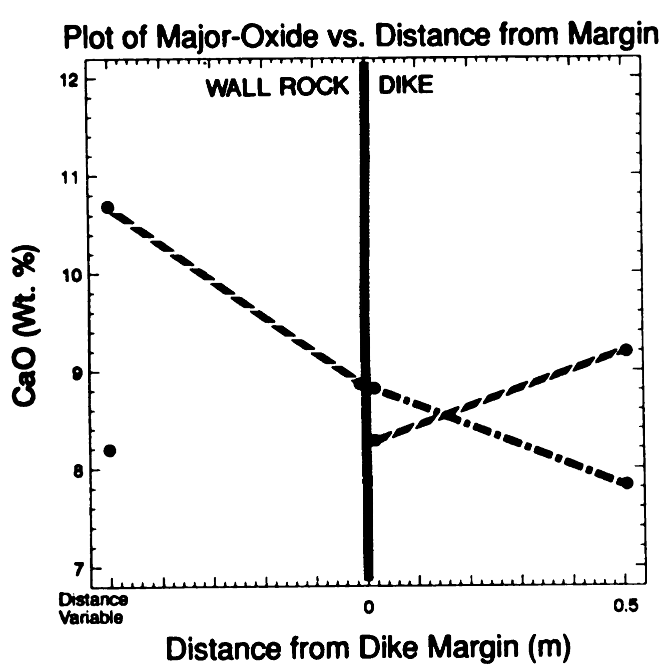
Republic dikes 1, 3, and 4 show enrichments of approximately two weight-percent K_2O, while dikes 2 and 5



EXPLANATION

Republic dike 1 · Republic dike 2 · Republic dike 3 · Republic dike 4 · Republic dike 5

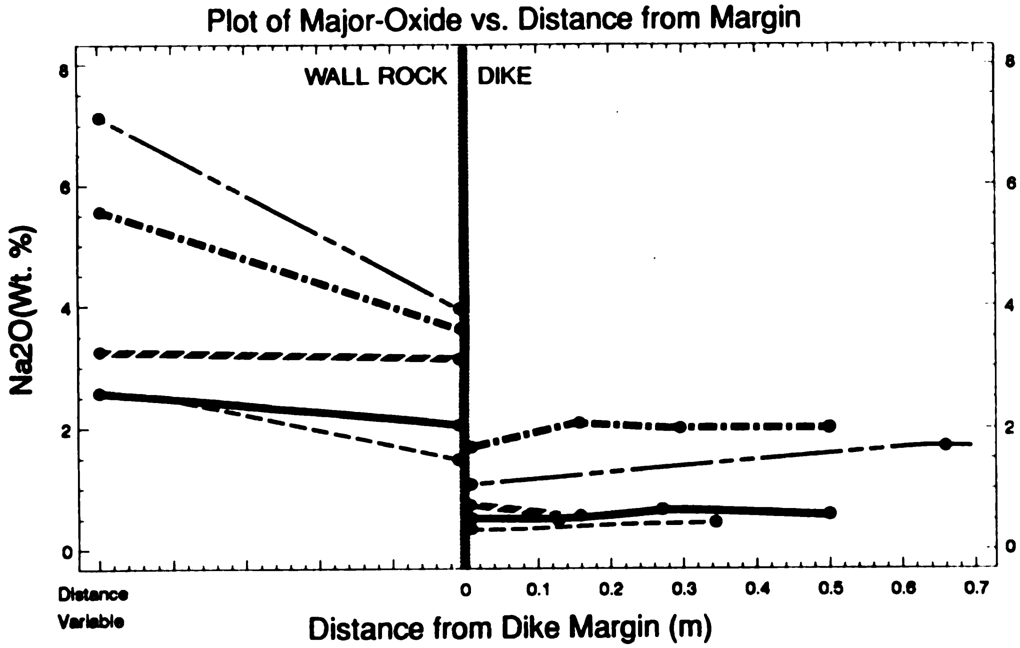
Figure 21a.--Plot of CaO vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

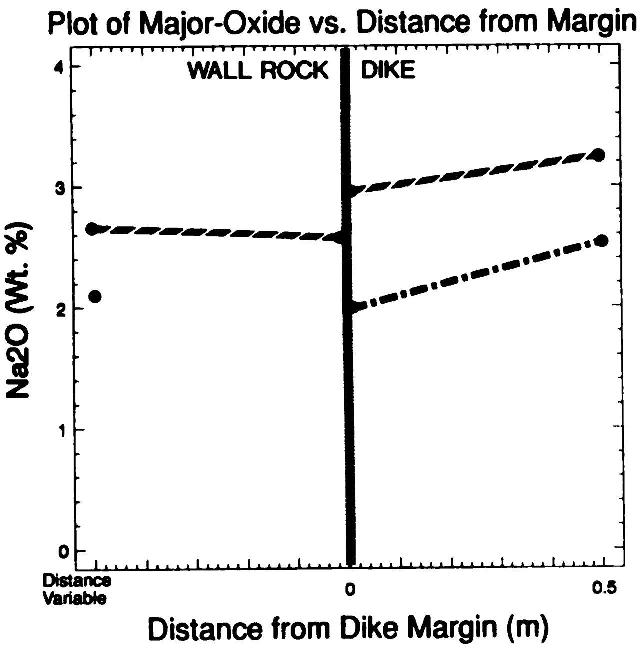
Figure 21b.--Plot of CaO vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

Figure 22a.--Plot of Na_2O vs. distance from dike margin for Republic area dikes.



EXPLANATION

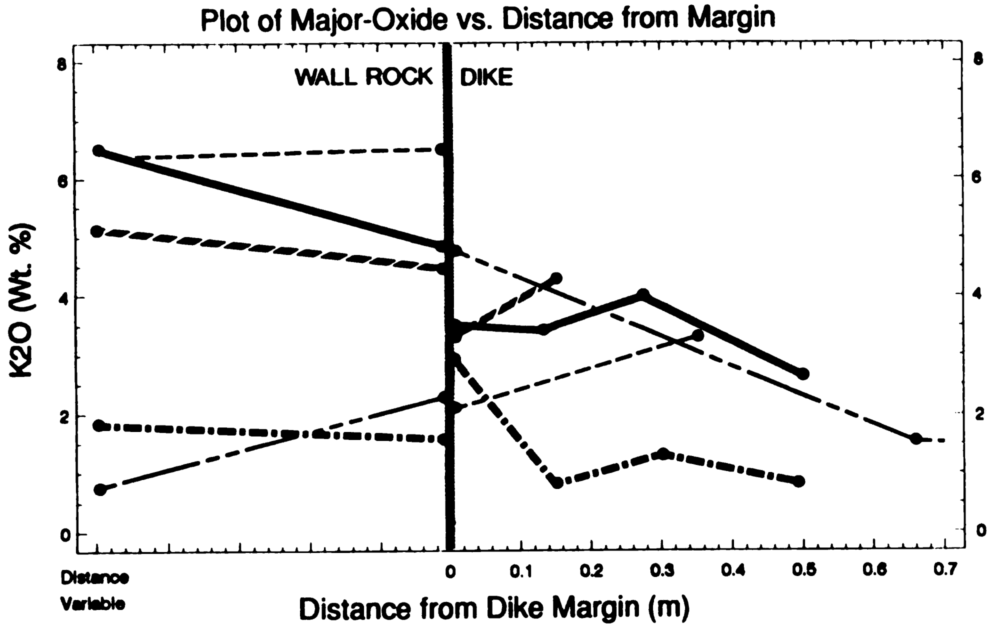
LHP E-W dike
LHP E-W wall rock
LHP N-S dike

Figure 22b.--Plot of Na_2O vs. distance from dike margin for Lighthouse Point dikes.

are depleted approximately one weight percent at the dike margins (Figure 23a). K_2O in the N-S LHP dike is depleted slightly, and nearly flat in the E-W dike (Figure 23b). Some potassium enrichment at the dike margins was anticipated, as a result of deformation-induced contamination from surrounding wall rock. Wall rock surrounding dikes 1 and 4 shows some depletion at the margins, while wall rock surrounding dike 3 shows a significant enrichment at the margin. Most potassium in these dikes is contained in biotite, and changes in modal concentrations of biotite primarily parallel the chemical trends.

Republic dikes 1 and 2 show small enrichments of TiO_2 and P_2O_5, while dikes 3, 4, and 5 show small depletions (Figures 24a, 25a), at the margins. In the LHP dikes, TiO_2 is slightly depleted and P_2O_5 is slightly enriched (Figures 24b, 25b). Studies of O'Hara (1990) and Glazner and Bartley (1991) showed many-fold enrichments of Ti and P which they interpreted as evidence of bulk-volume loss, since these elements are normally conserved. The behavior of TiO_2 and P_2O_5 in these dikes fails to support any significant volume change.

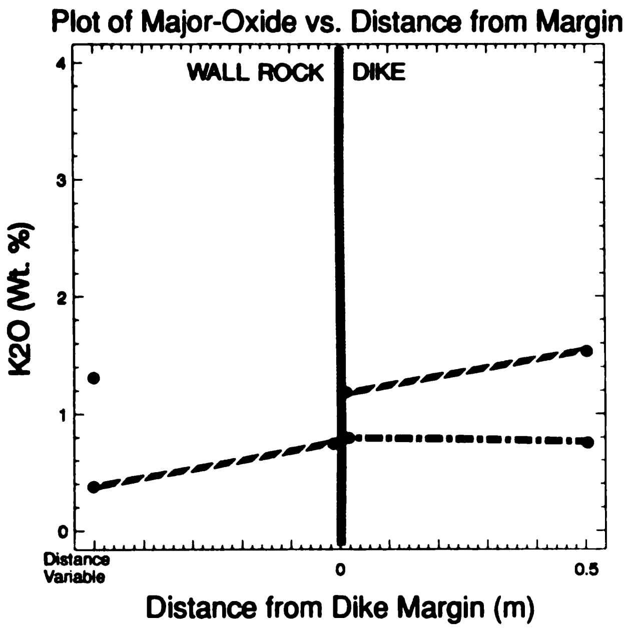
MnO in Republic dikes 1 and 5, and both LHP dikes is enriched at the dike margins, and depleted in dike 4, while the trends of the remaining dikes are nearly-flat (Figures 26a,b).



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

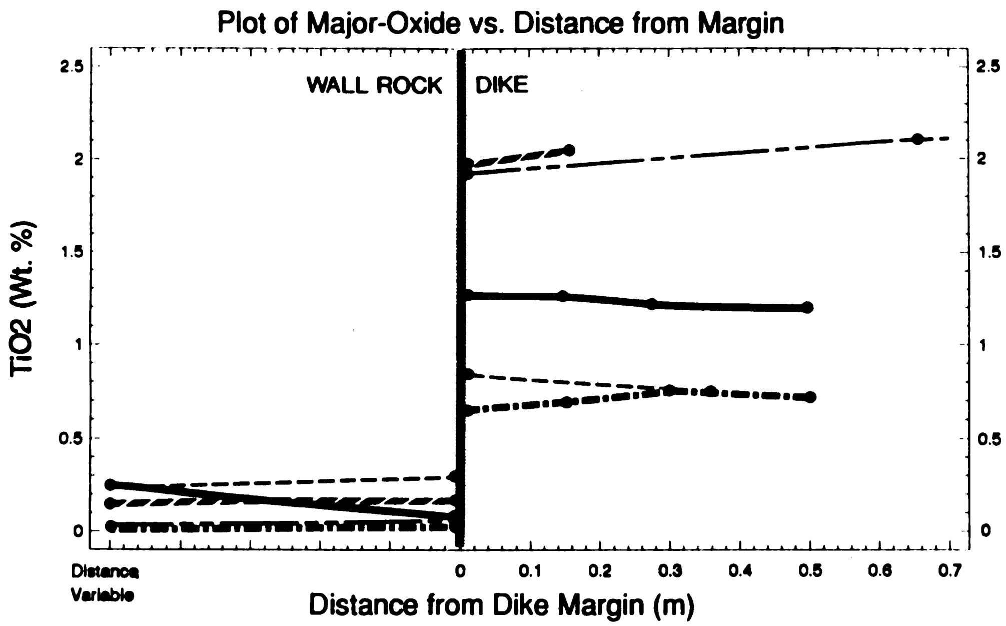
Figure 23a.--Plot of K_2O vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

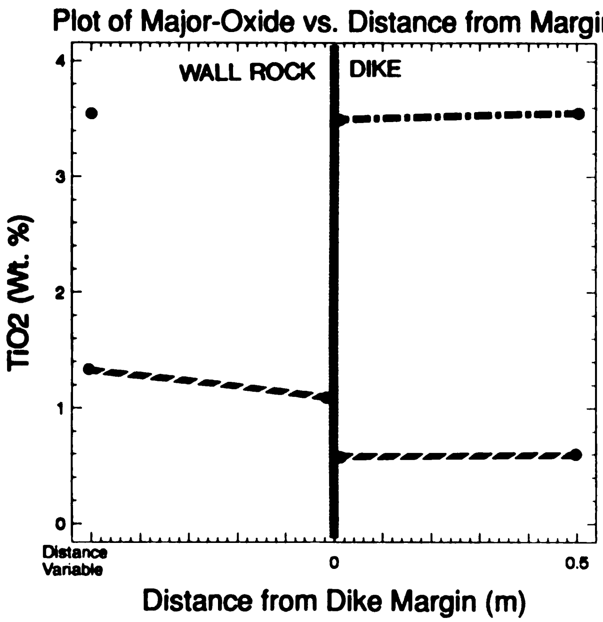
Figure 23b.--Plot of K_2O vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

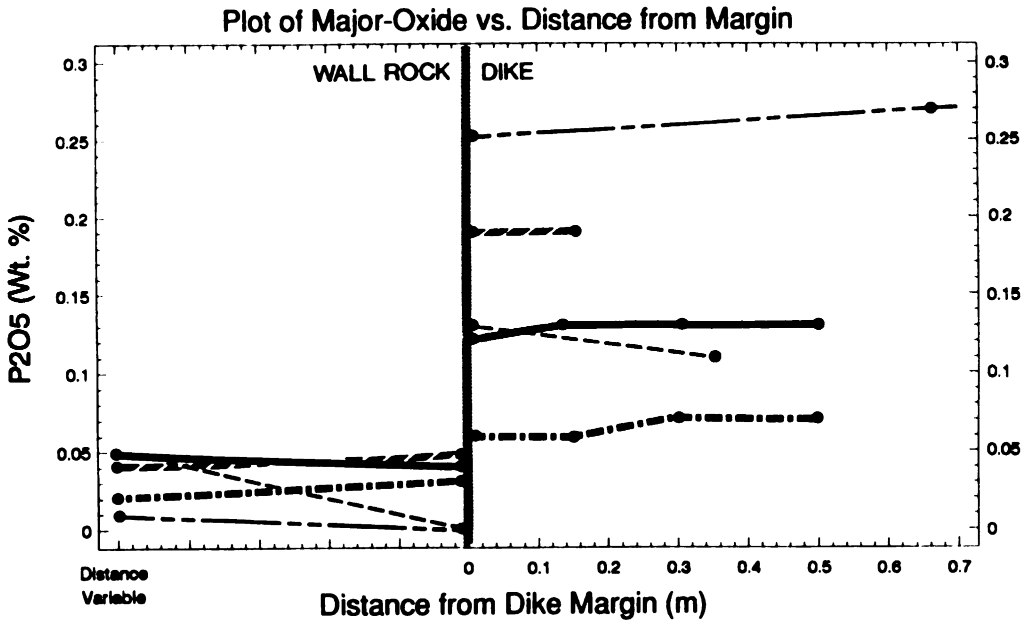
Figure 24a.--Plot of TiO_2 vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

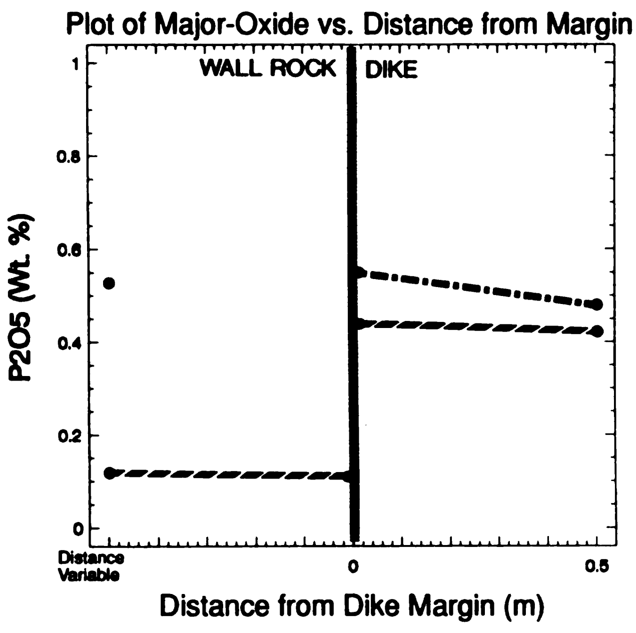
Figure 24b.--Plot of TiO_2 vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

Figure 25a.--Plot of P_2O_5 vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

Figure 25b.--Plot of P_2O_5 vs. distance from dike margin for Lighthouse Point dikes.

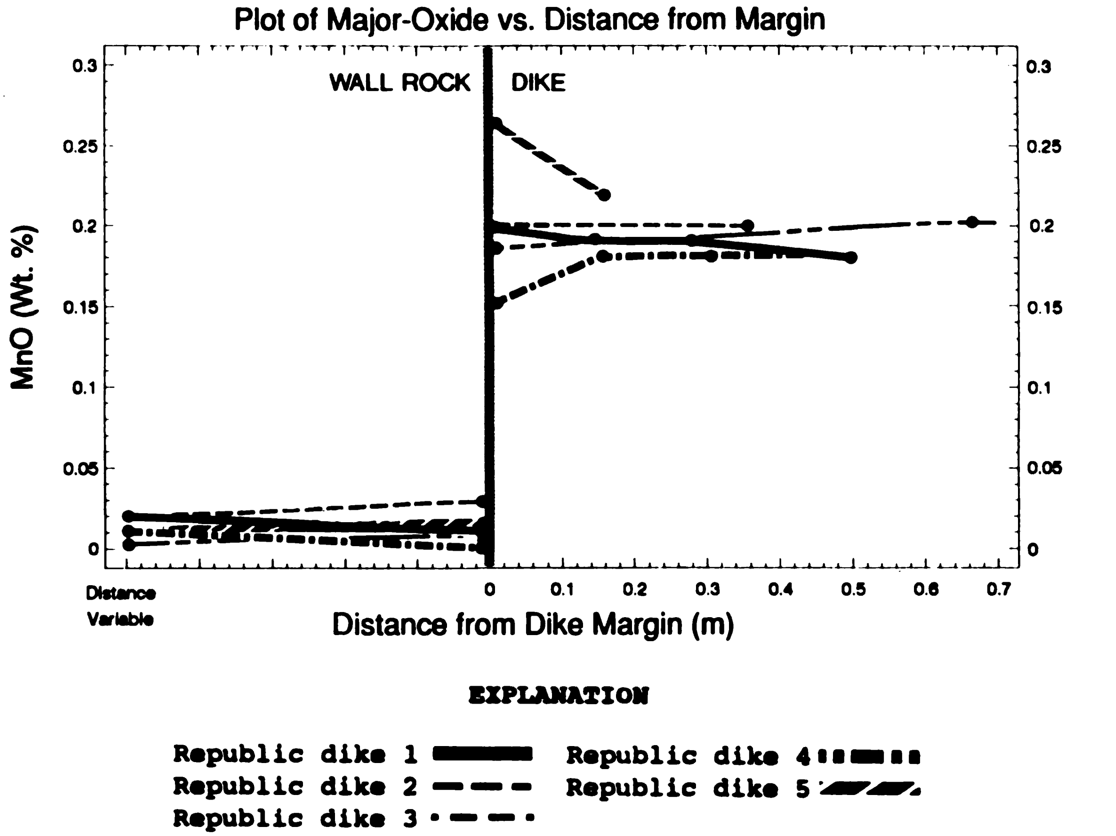


Figure 26a.--Plot of MnO vs. distance from dike margin for Republic area dikes.

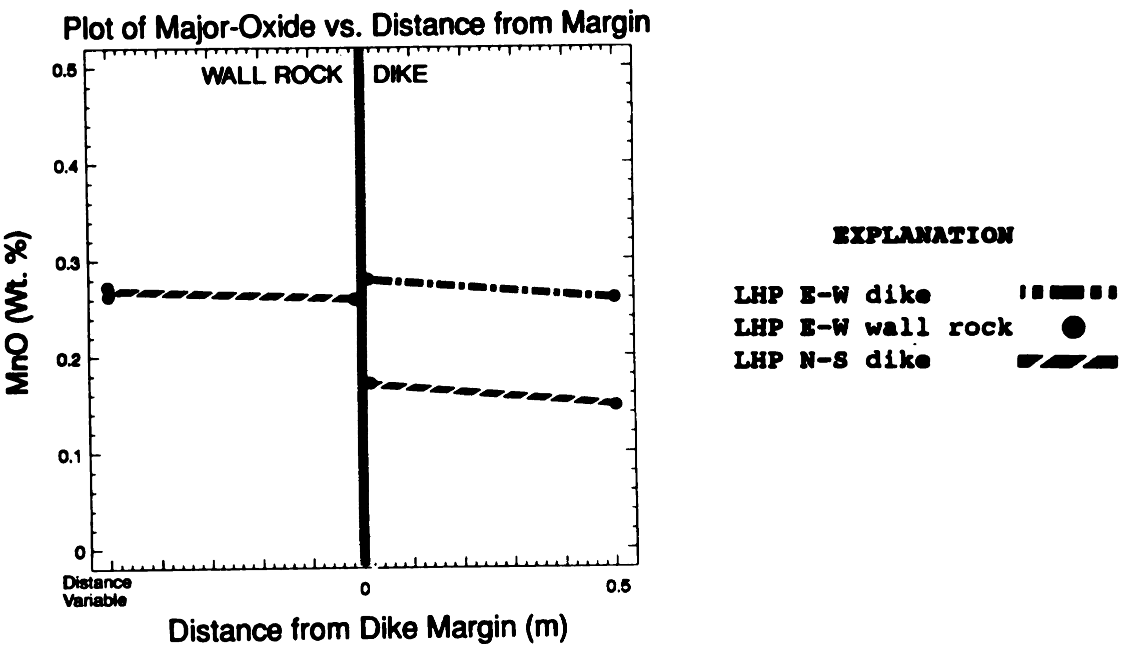


Figure 26b.--Plot of MnO vs. distance from dike margin for Lighthouse Point dikes.

Trace Elements

Several trace elements are shown to be conserved in metamorphic systems. Although trace elements comprise a only small portion of the whole rock, their trends are useful in volume loss studies. Large enrichments in normally-conserved elements could be interpreted as evidence of volume loss. Flat trends for normally-conserved elements could be interpreted as evidence of little or no volume loss, or an indication that the element was non-conserved.

Republic dike 2 has an approximately six-fold enrichment in Cr, while trends of the other dikes are nearly flat (Figures 27a,b). The very large enrichment of Cr in dike 2 may indicate volume loss, although dike 2 is highly-mafic, and concentrations of chrome may be related to the original chemistry of the dike. Glazner and Bartley (1991) also showed large Cr enrichments in their study.

Republic dikes 2 and 4 show a large enrichment in Ni, while trends for the other Republic dikes are nearly flat to slightly-enriched, and the LHP dikes show depletions as large as two-fold (Figure 28a,b). Enrichment in Ni in dikes 2 and 4 may indicate volume loss, particularly when accompanied by enrichments in other trace elements.

Cu falls below the acceptable detection limits of 50 ppm in the Republic dikes and is not considered for this analysis. Both LHP dikes show enrichments in Cu (Figure

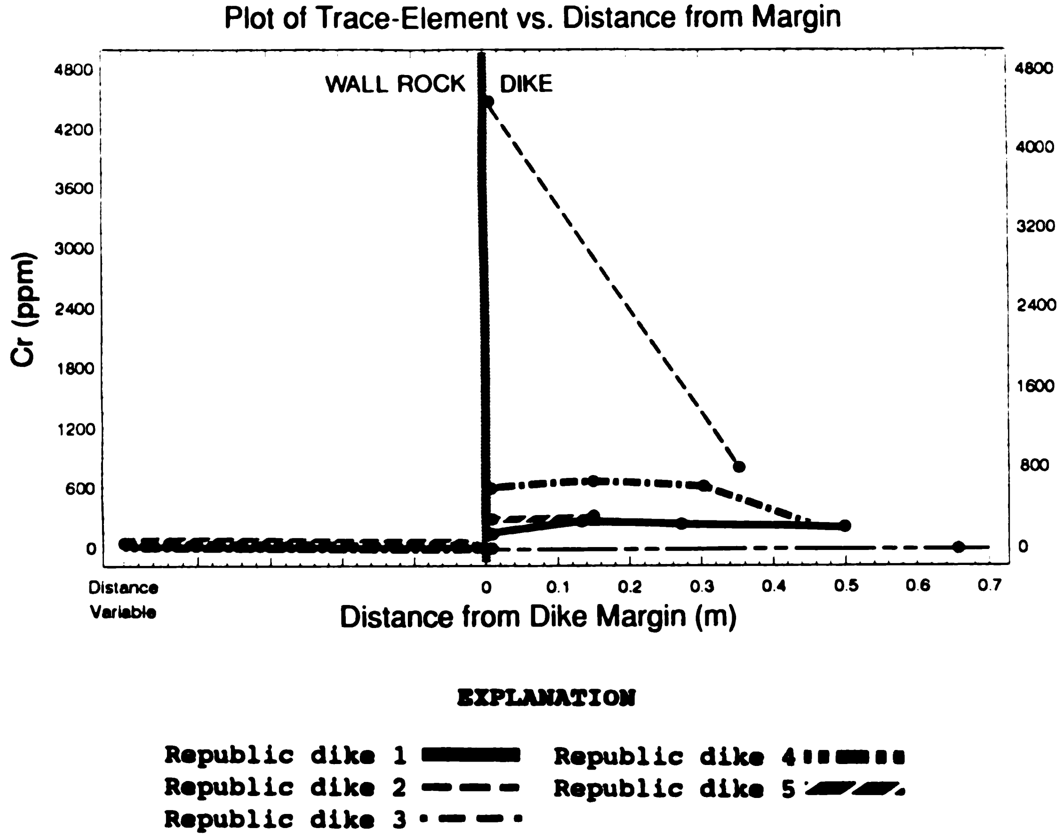


Figure 27a.--Plot of Cr vs. distance from dike margin for Republic area dikes.

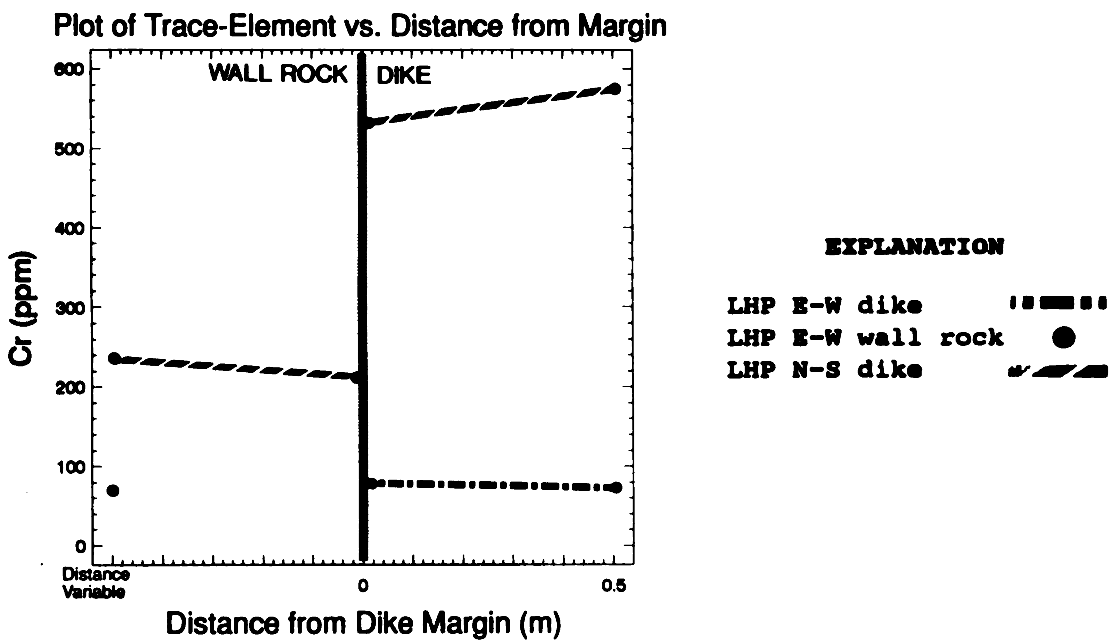


Figure 27b.--Plot of Cr vs. distance from dike margin for Lighthouse Point dikes.

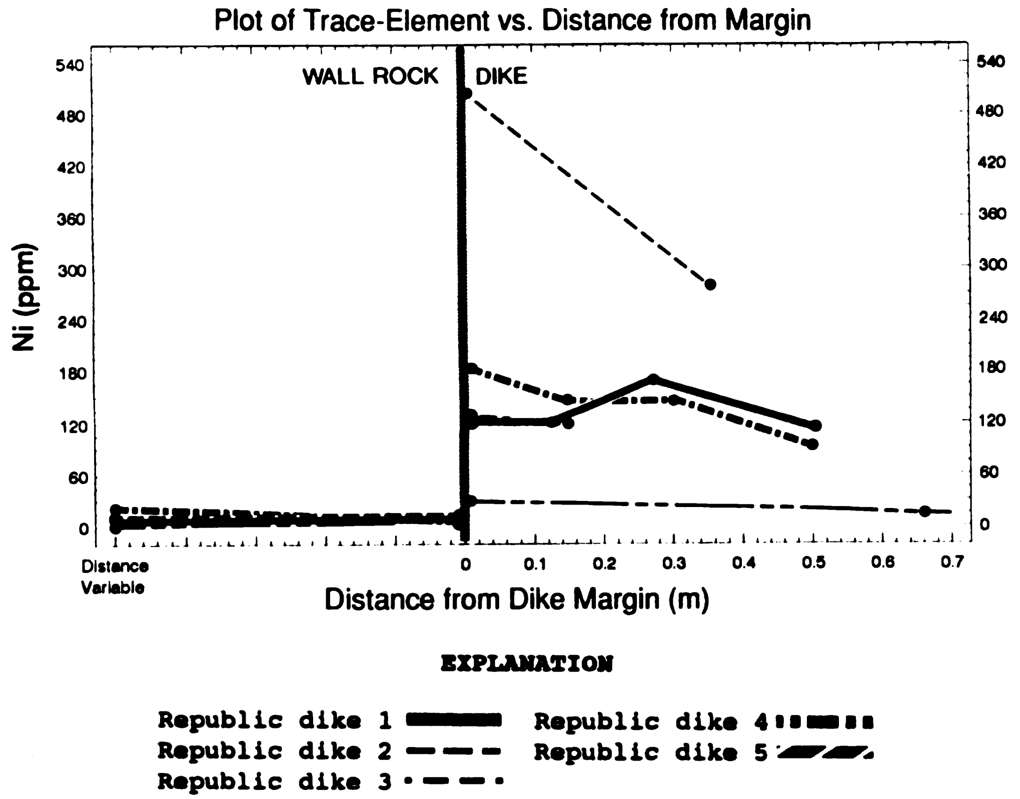


Figure 28a.--Plot of Ni vs. distance from dike margin for Republic area dikes.

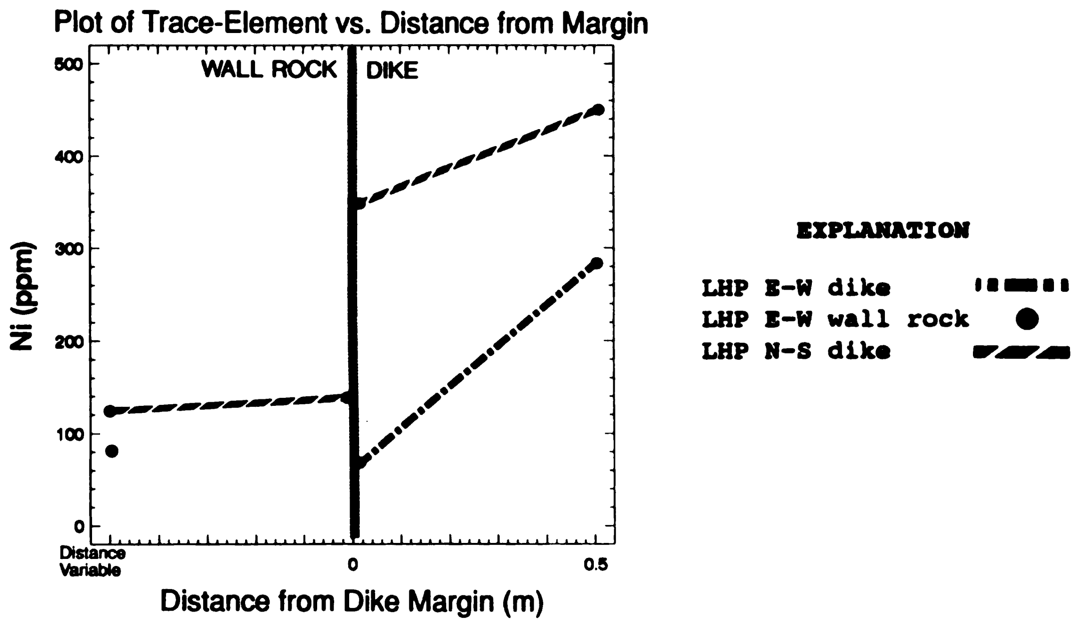


Figure 28b.--Plot of Ni vs. distance from dike margin for Lighthouse Point dikes.

29). The N-S trending dike shows enrichment of dike and wall rock, at the margin.

Republic dikes 3 and 4 show an enrichment in Zn, while the remaining dikes show depletions (Figures 30a,b). Enrichment in Zn may indicate volume loss, particularly when it accompanies enrichments in other trace elements.

As anticipated, the trends for Rb are nearly identical to those of K_2O. Republic dikes 1, 3, and 4 show enrichments, while the remaining dikes are depleted (Figures 31a,b).

Calcium and Sr substitute for one another, and their trends should be nearly identical. For unknown reasons, Republic dike 2 and the E-W LHP dike have opposing Ca and Sr trends. Republic dikes 1, 3, and 4, and both LHP dikes show depletions in Sr as large as five-fold, while dikes 2 and 5 show slight enrichments (Figure 32a,b). As anticipated, Sr trends complement those of Rb.

Republic dikes 2 and 4, and the E-W LHP dike show enrichments in Y, while dike 1 shows a depletion, and the remaining dikes have approximately flat trends (Figures 33a,b). O'Hara (1990) suggested that a three-fold enrichment in Y in his study was evidence for volume loss, and dike 2 has a two-fold enrichment, but enrichment in dike 4 and the E-W LHP dike are of a much smaller magnitude.

Republic dikes 1, 2, and 4 show slight enrichments in Zr, while remaining dikes have slight depletions (Figures 34a,b). O'Hara (1990) suggested that large enrichments in

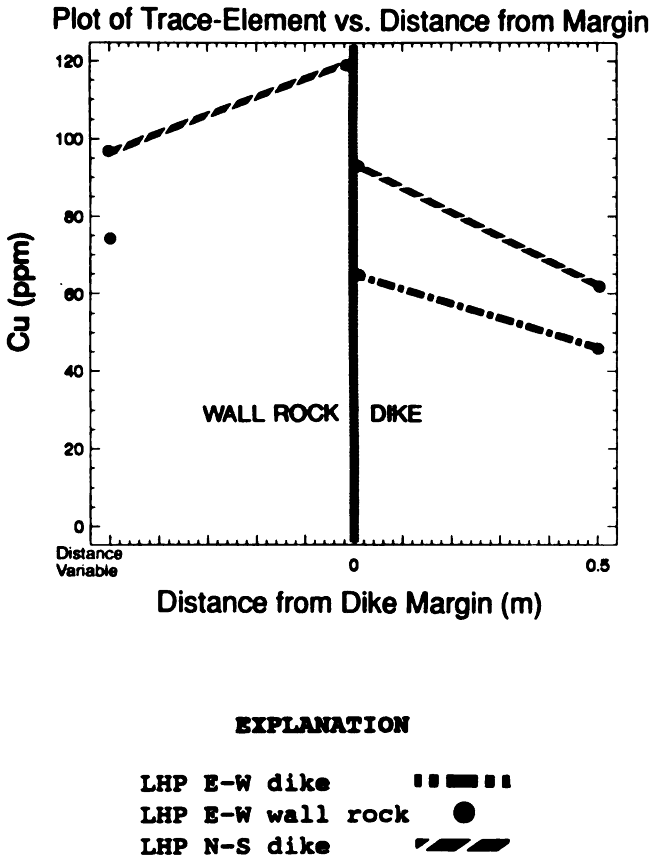


Figure 29.--Plot of Cu vs. distance from dike margin for Lighthouse Point dikes.

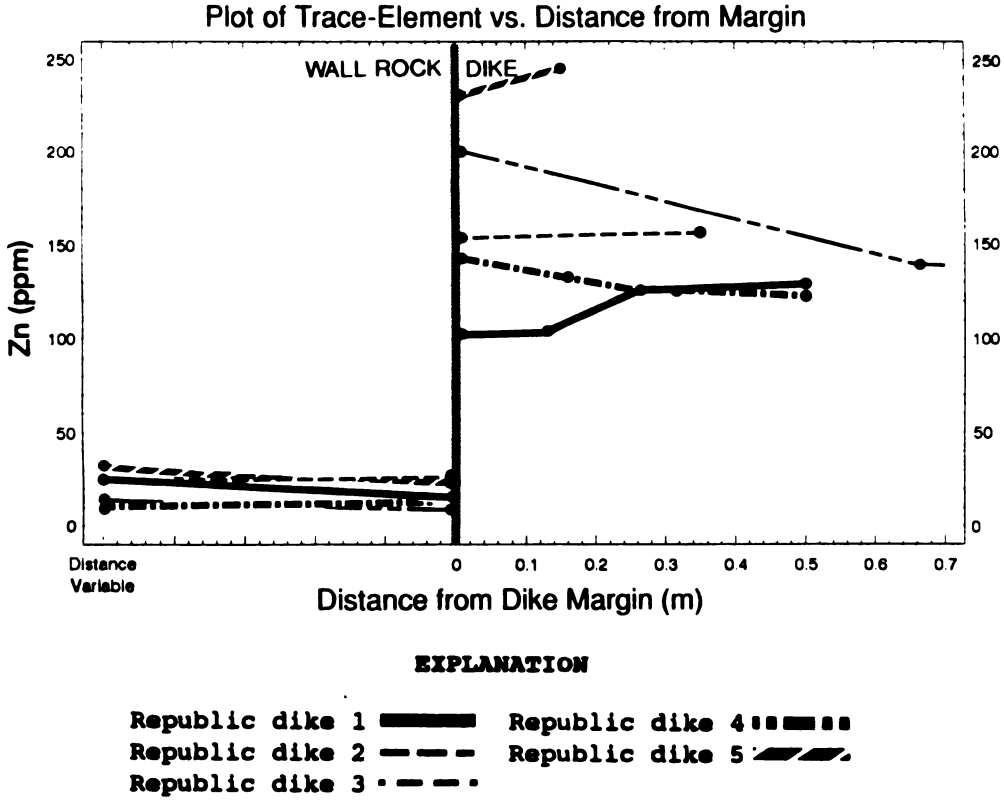


Figure 30a.--Plot of Zn vs. distance from dike margin for Republic area dikes.

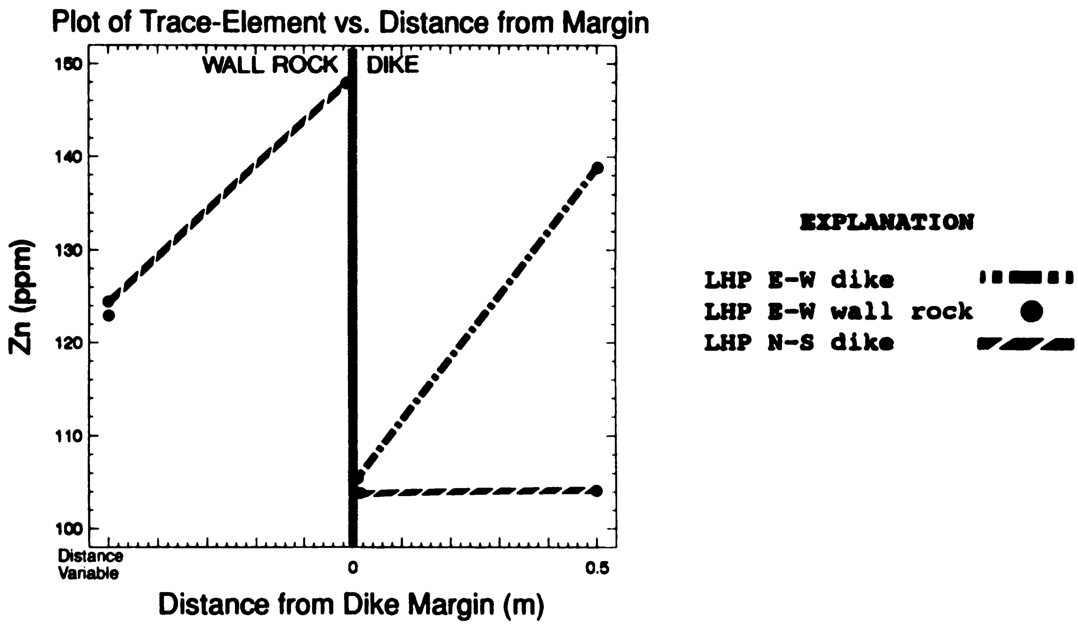
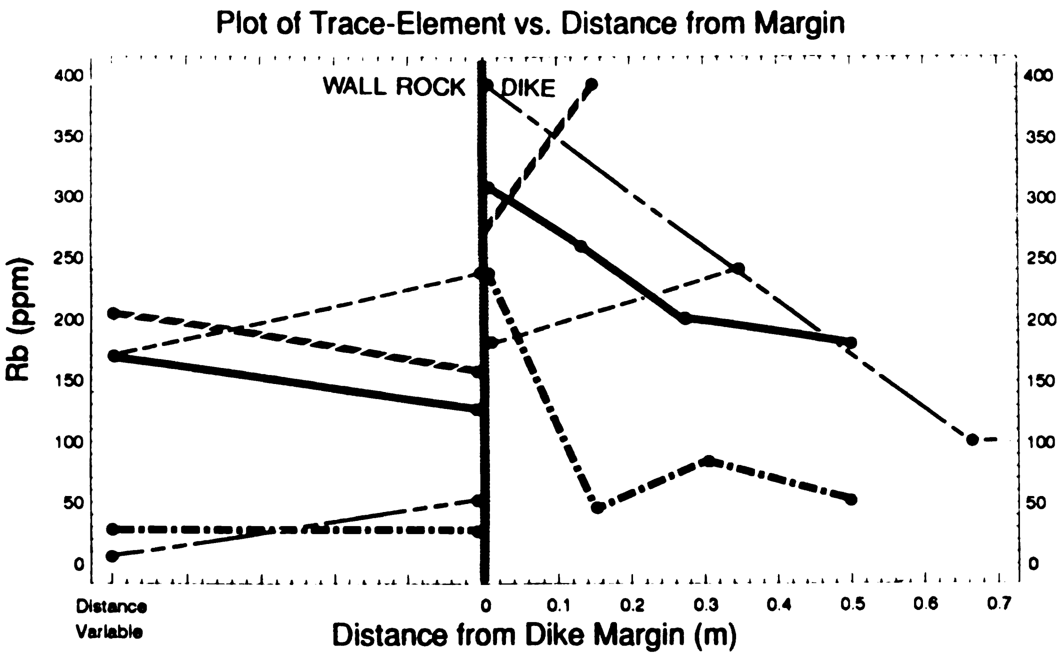


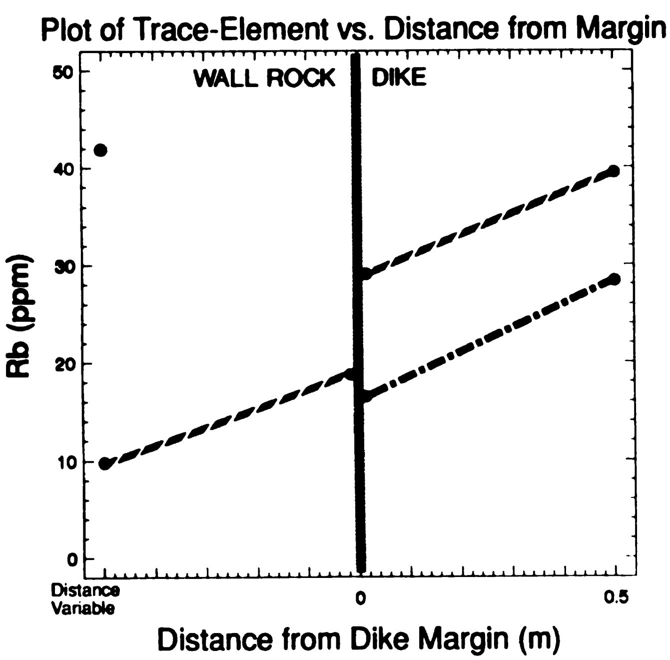
Figure 30b.--Plot of Zn vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

Figure 31a.--Plot of Rb vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

Figure 31b.--Plot of Rb vs. distance from dike margin for Lighthouse Point dikes.

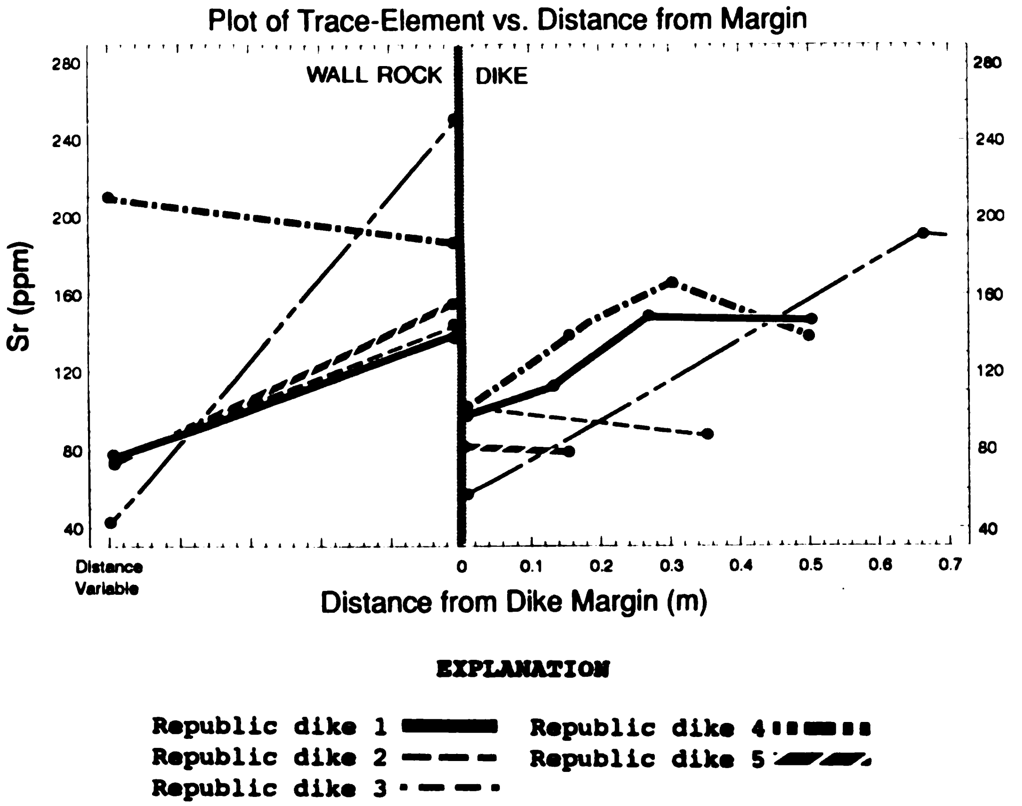


Figure 32a.--Plot of Sr vs. distance from dike margin for Republic area dikes.

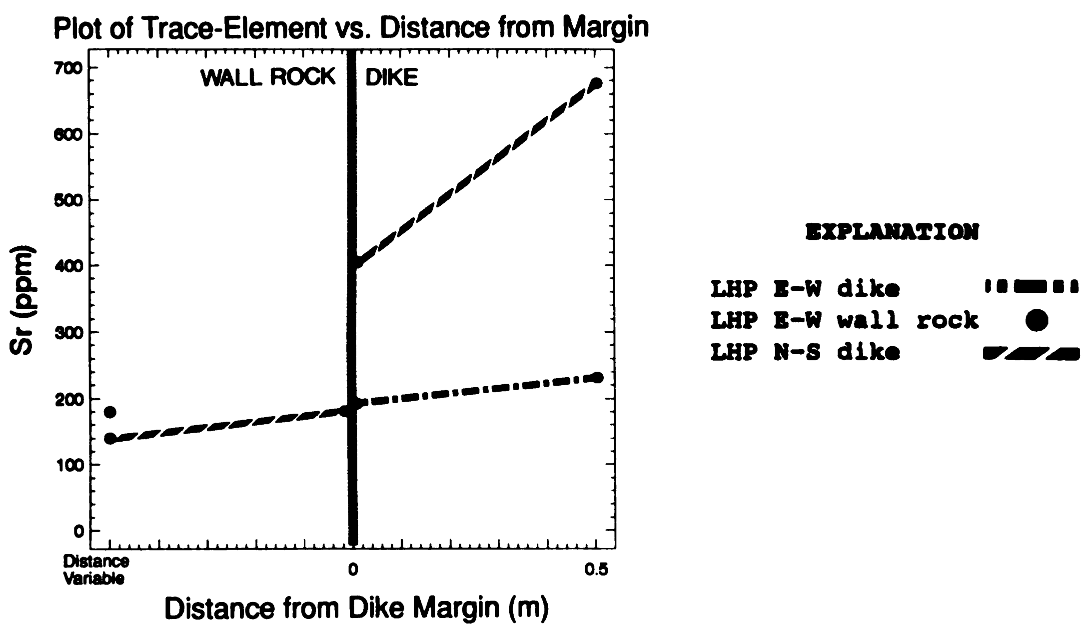


Figure 32b.--Plot of Sr vs. distance from dike margin for Lighthouse Point dikes.

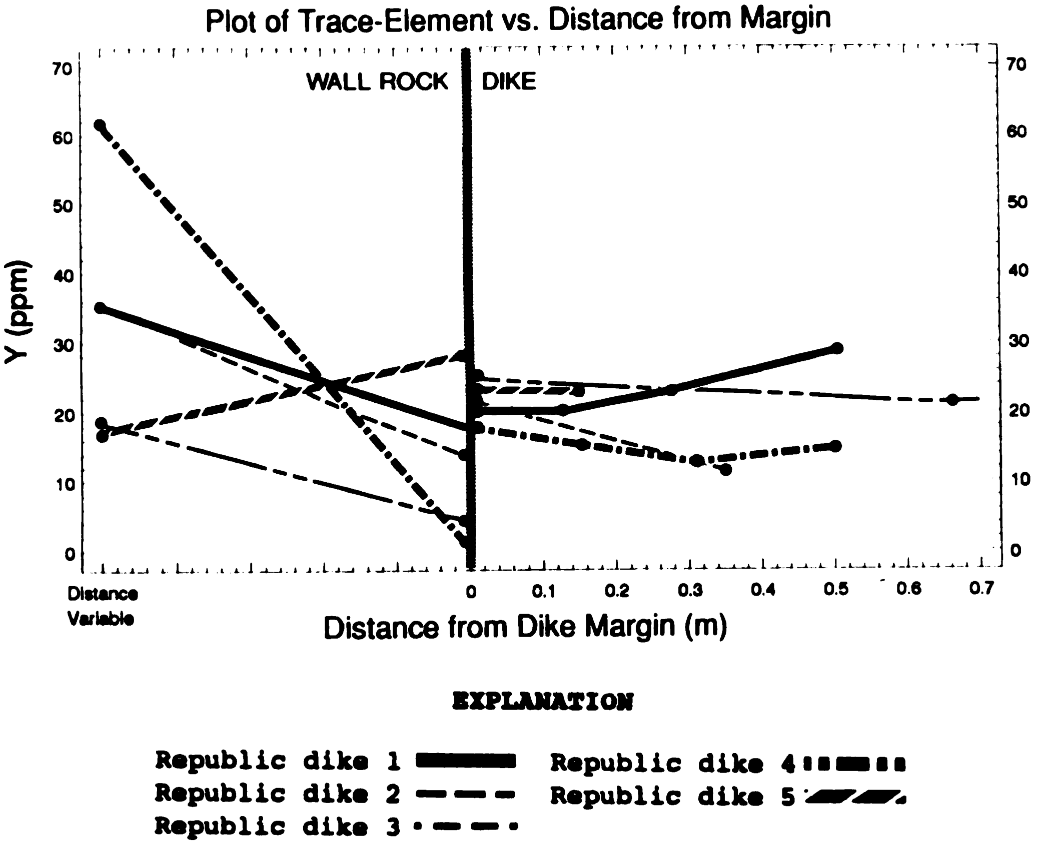


Figure 33a.--Plot of Y vs. distance from dike margin for Republic area dikes.

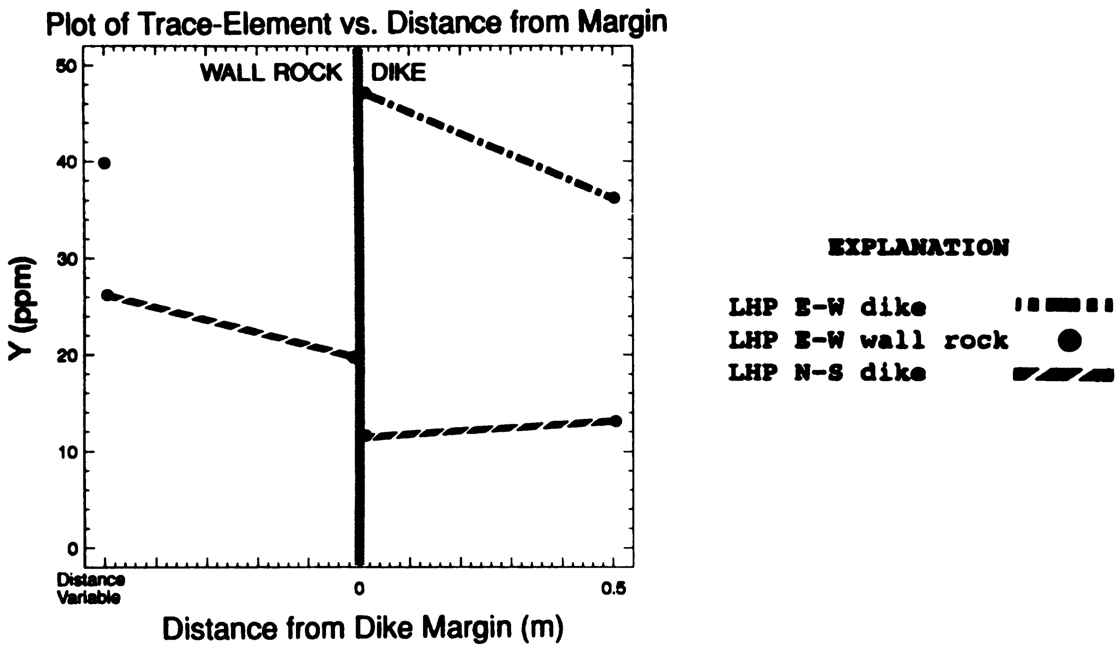
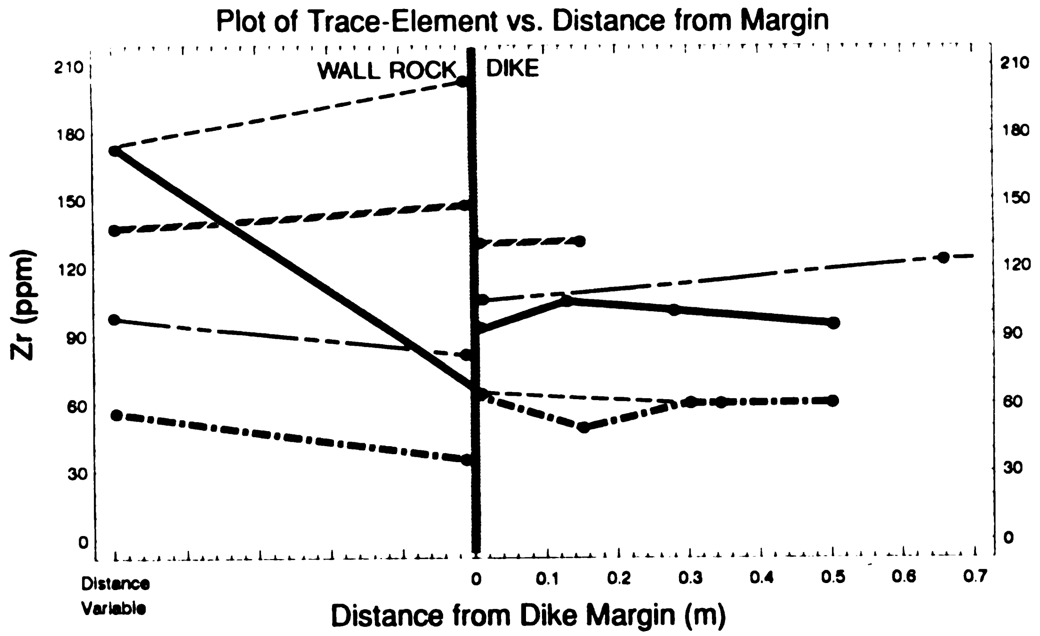


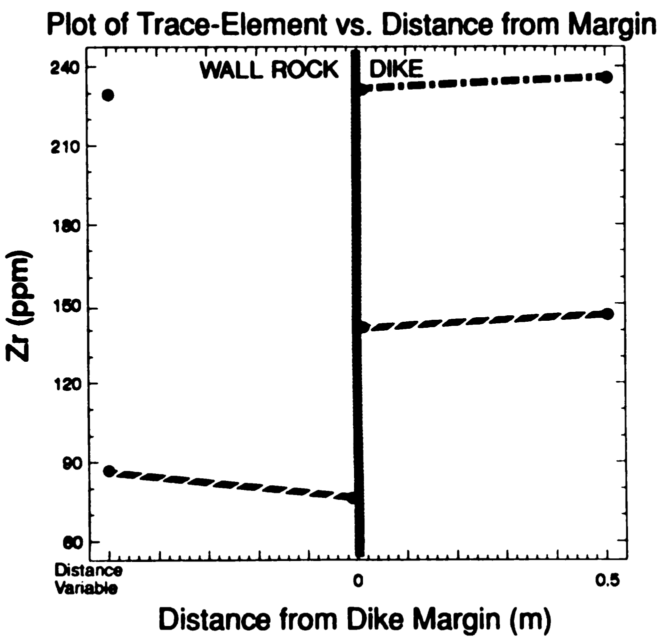
Figure 33b.--Plot of Y vs. distance from dike margin for Lighthouse Point dikes.



EXPLANATION

Republic dike 1
Republic dike 2
Republic dike 3
Republic dike 4
Republic dike 5

Figure 34a.--Plot of Zr vs. distance from dike margin for Republic area dikes.



EXPLANATION

LHP E-W dike
LHP E-W wall rock
LHP N-S dike

Figure 34b.--Plot of Zr vs. distance from dike margin for Lighthouse Point dikes.

Zr were evidence for volume loss, but the enrichments in the dikes of this study are quite small.

Republic dikes 2 and 3 show slight enrichments in Nb, while dikes 1, 4, 5, and the E-W LHP dike show depletions (Figures 35a,b). Nb was not present in the samples from the N-S LHP dike.

Ba falls below the acceptable detection limits of 250 ppm in portions of every Republic dike, and analyses must be used with caution. Republic dikes 1, 3, and 4 show enrichments in Ba, while the remaining dikes show depletions (Figures 36a,b). The enrichments in the Republic dikes range up to six-fold (dike 3). Depletions in the Republic dikes are as large as two-fold, while depletion in the LHP dikes is of a much smaller magnitude.

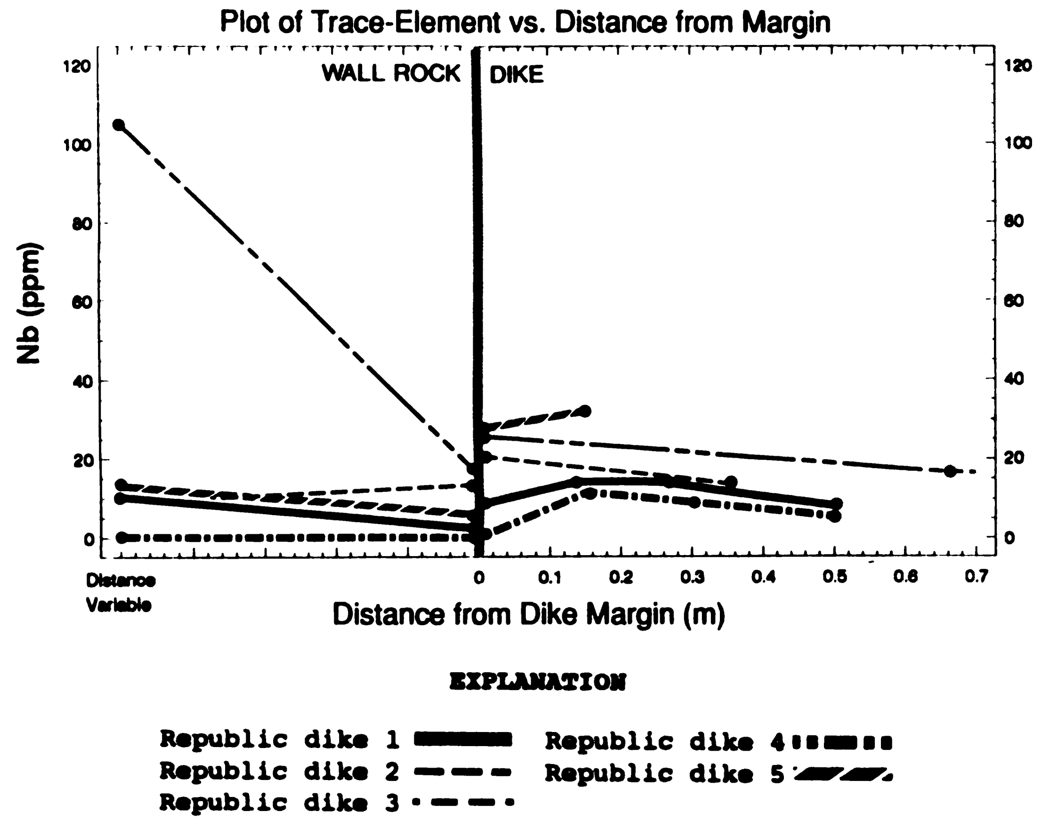


Figure 35a.--Plot of Nb vs. distance from dike margin for Republic area dikes.

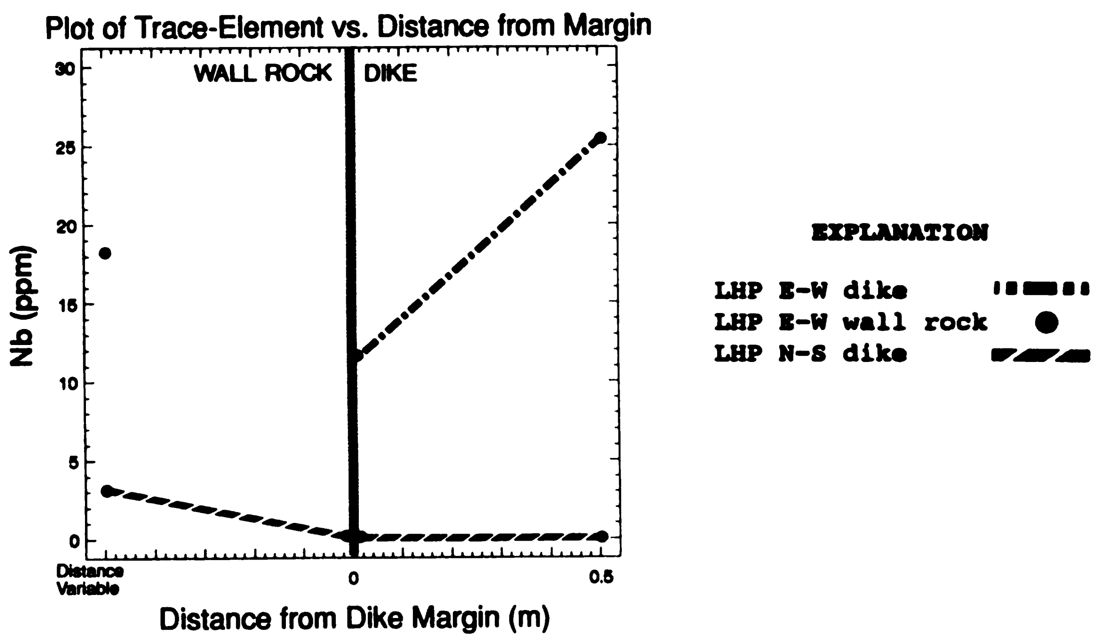


Figure 35b.--Plot of Nb vs. distance from dike margin for Lighthouse Point dikes.

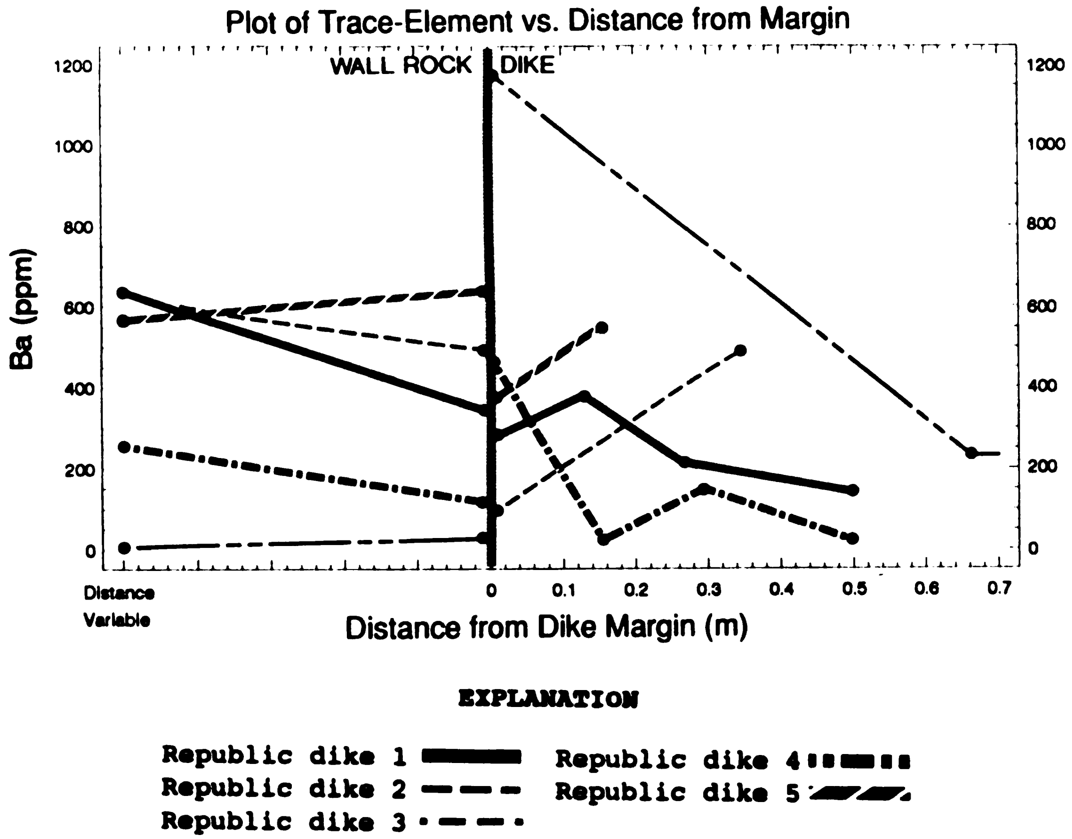


Figure 36a.--Plot of Ba vs. distance from dike margin for Republic area dikes.

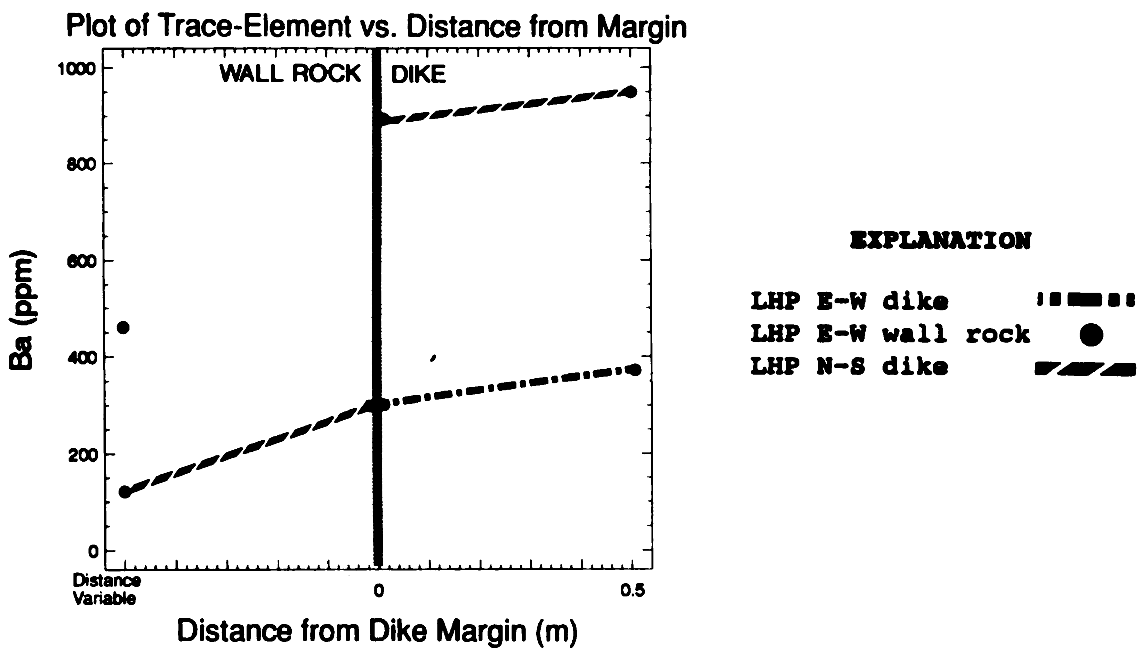


Figure 36b.--Plot of Ba vs. distance from dike margin for Lighthouse Point dikes.

EFFECT OF SHEAR STRAIN ON BULK-ROCK CHEMISTRY

The mineralogy of foliated Republic area dikes varies from dike interior to dike margin. In margin samples, there is typically a higher modal percentage of mafic phases, such as biotite, chlorite, and amphibole, and a lower modal percentage of felsic phases, primarily plagioclase. As noted in the section on petrography, modal variations are accompanied by other changes including degree of recrystallization and formation of foliation.

As noted in the section on shear strain analysis, some very large displacements occurred as a result of Penokean shearing. This section, which compares bulk-rock chemistry to shear strain for Republic area dikes 1, 2, and 5, illustrates that little change in bulk-rock chemistry accompanies some very large shear strains.

The condition of the dikes in outcrop determined the usefulness of a particular dike for shear strain measurements. Republic dikes 1, 2, and 5 were chosen for this analysis because each had a well-developed foliation which could be easily measured and interpreted. The foliation of Republic dikes 3 and 4 was poorly exposed, and neither dike was utilized for this portion of the study.

This was unfortunate, as both dikes had large variations in mineralogy and bulk-rock chemistry.

Major oxides used in this section were chosen after reviewing XRF analyses and plots of bulk-rock chemistry vs. distance from the dike margin. Major oxides (in weight percent) are plotted as a function of shear strain (gamma units). In other volume loss studies, Ti and P have been considered conserved (O' Hara, 1990; Glazner and Bartley, 1991), with enrichments as large as three-fold noted. There are only small enrichments in Ti and P for dikes 1 and 2, and MnO comprises only a small fraction (<0.3 weight percent) of the total bulk-rock, and they were excluded from this portion of the study. Trace elements were discussed in the previous section and are not utilized in this portion of the study.

The diagrams for dike 1 are based on four data collection points across the dike, diagrams for dikes 2 and 5 are based on two data collection points per dike, at the dike margin and the approximate center of each dike. Although data for the dikes is sparse, these end points should reflect enrichment or depletion within those dikes. The trends described by the diagrams are generalized. In each diagram, the shear strain increases from left to right.

Republic dike 1

A trend of select major oxides as a function of shear-strain is shown in Figure 37. Data is from four sampling locations, from the dike center to the dike margin. The dike sampling sites roughly correspond with strain measurement locations on this dike. The trends shown in the diagrams reflect analyses from all four data points.

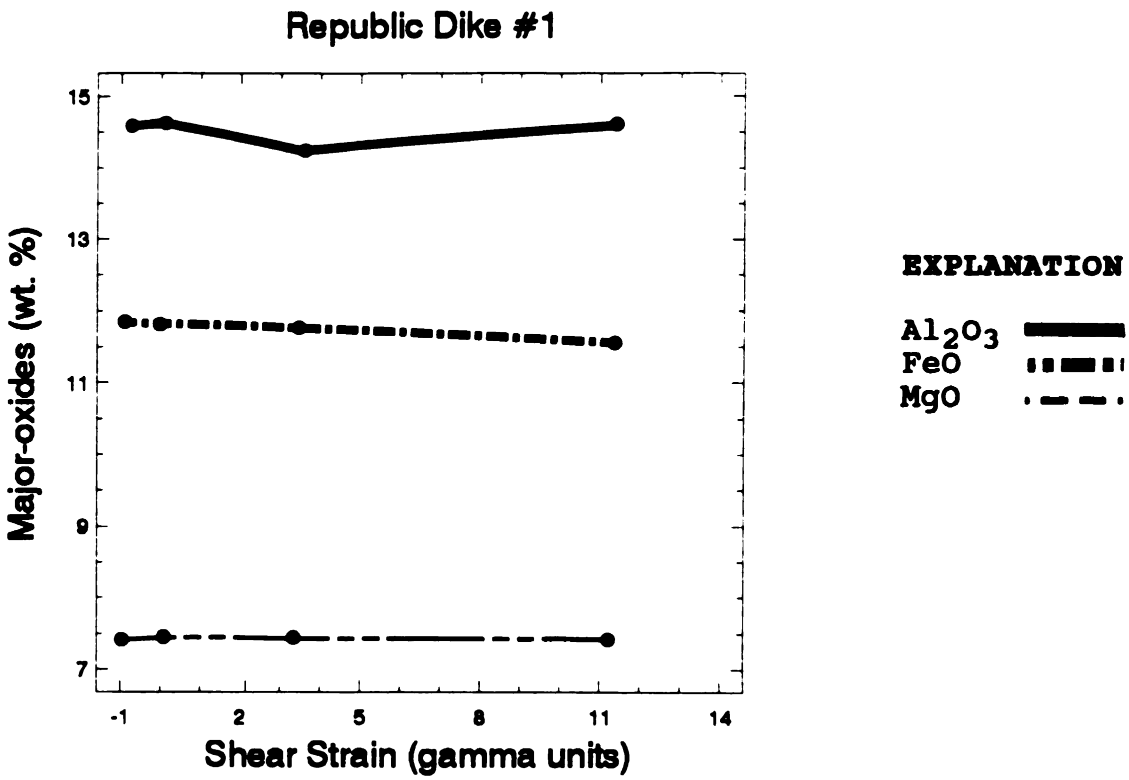
Figure 37 shows little variation for five of the oxides analyzed. In spite of large strain measurements, a comparison of low- and high-strain endpoints shows a depletion of approximately 1.5 percent for CaO and less than one weight percent change for the other oxides.

Total strain from margin to center of the dike was 10.9 gamma units, which translated to an 1100% extension along the principal strain axis.

Analysis of select major-oxides from this section will be combined with other observations in the discussion, but these data indicate that little chemical change accompanies increasing strain in this dike, with the exception of CaO.

Republic dike 2

A generalized trend of select major-oxides as a function of shear-strain is shown in Figure 38. Data is from two sampling locations, dike margin and approximate



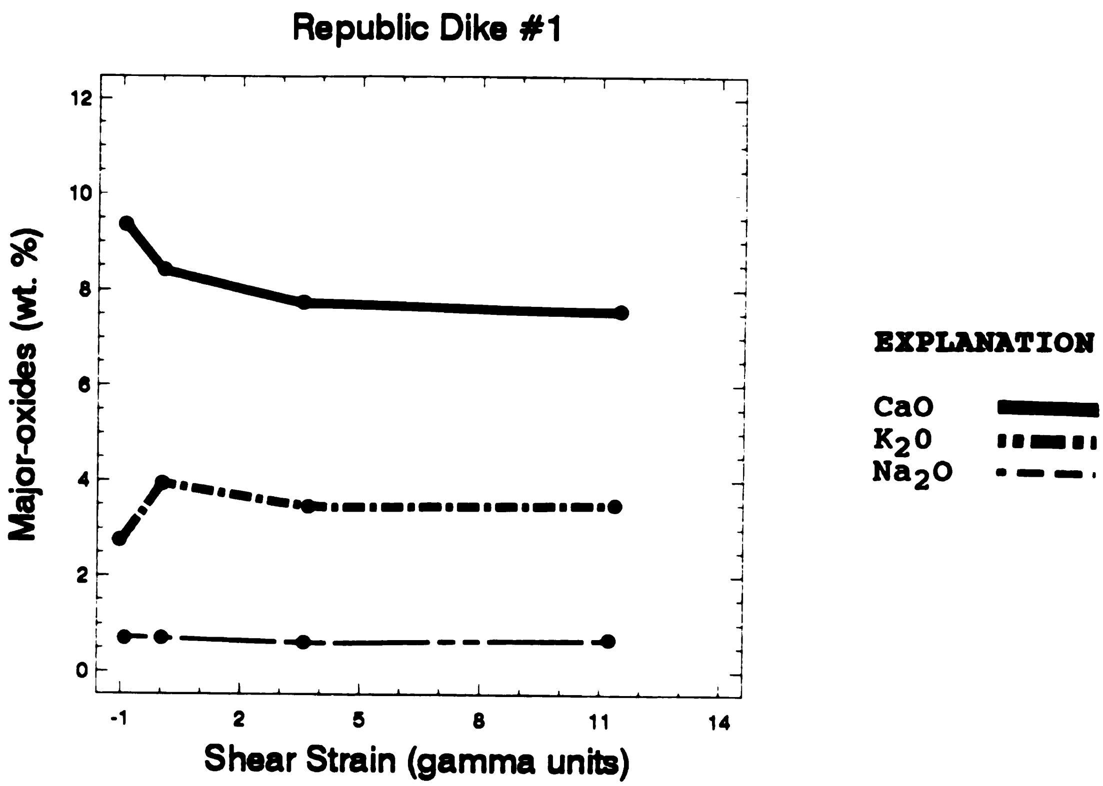
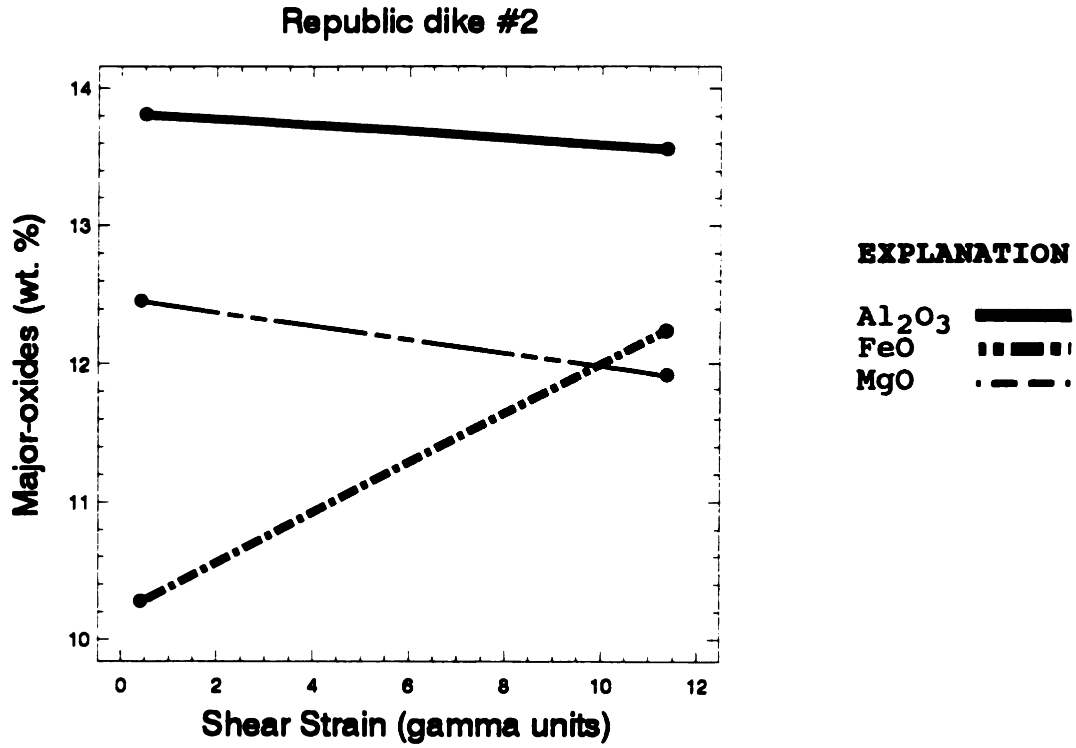


Figure 37.--Plot of major-oxides vs. shear strain, Republic dike 1.



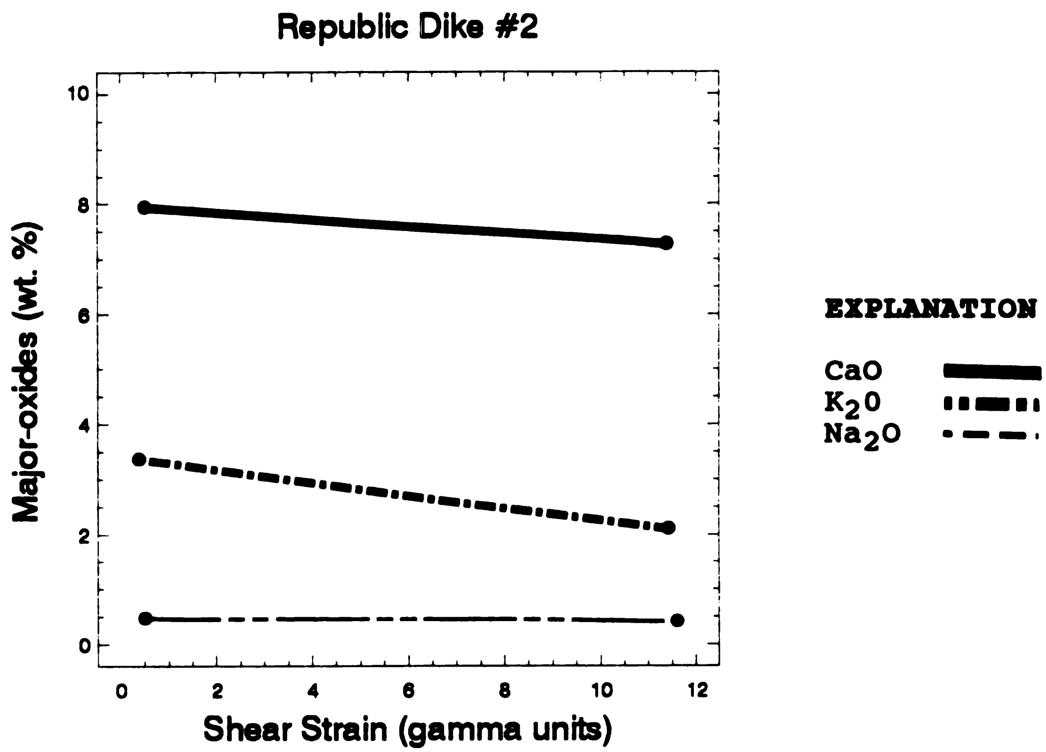


Figure 38.--Plot of major-oxides vs. shear strain, Republic dike 2.

dike center. The dike sampling sites roughly correspond with strain measurement locations on this dike.

Figure 38 shows very different major-oxide trends from those of dike 1. A comparison of low- and high-strain regimes shows a greater than two weight-percent enrichment in FeO, and one to less than one weight-percent depletion's of Al_2O_3, MgO, CaO, and K_2O. The trend of Na_2O is nearly flat.

Other Republic dikes have larger variations in some oxides, particularly CaO, but the consistency of depletion of Al_2O_3, MgO, CaO, and K_2O in this dike is notable. Coinciding with depletions in major oxides, are enrichments in Ti, P, Cr, Ni, Y, Zr, and Nb, noted in the previous section.

Total strain in this dike was 13.8 gamma units, which translated to a 1400% extension along the principal strain axis. These strain measurements are for the entire width of this dike, and are somewhat higher than those of dikes 1 and 5 where only a portion of the dike was measured.

Analysis of select major-oxides from this section will be combined with other observations in the discussion, but these data indicate that distinct chemical changes accompany increasing strain in this dike.

Republic dike 5

A generalized trend of select major-oxides as a function of shear-strain is shown in Figure 39. Data is from two sampling locations, dike margin and approximate dike center. The sampling sites for this dike directly correspond with strain measurements locations on this dike.

Figure 39 shows some interesting trends for the six oxides. A comparison of low- and high-strain regimes shows a greater than two weight-percent enrichment in CaO, a slight enrichment in Na_2O, and one to less than one weight-percent depletions of Al_2O_3, FeO, MgO, and K_2O. The trends of the major-oxides are opposite those of other Republic dikes.

Total strain from margin to center of the dike was 4.6 gamma units, which translated to a 500% extension along the principal strain axis.

Analysis of select major-oxides from this section will be combined with other observations in the discussion, but these data indicate that distinct chemical changes accompany increasing strain in this dike. The width of this dike and orientation to Penokean stress directions may account for the unusual trends, although the extent of influence is unknown.

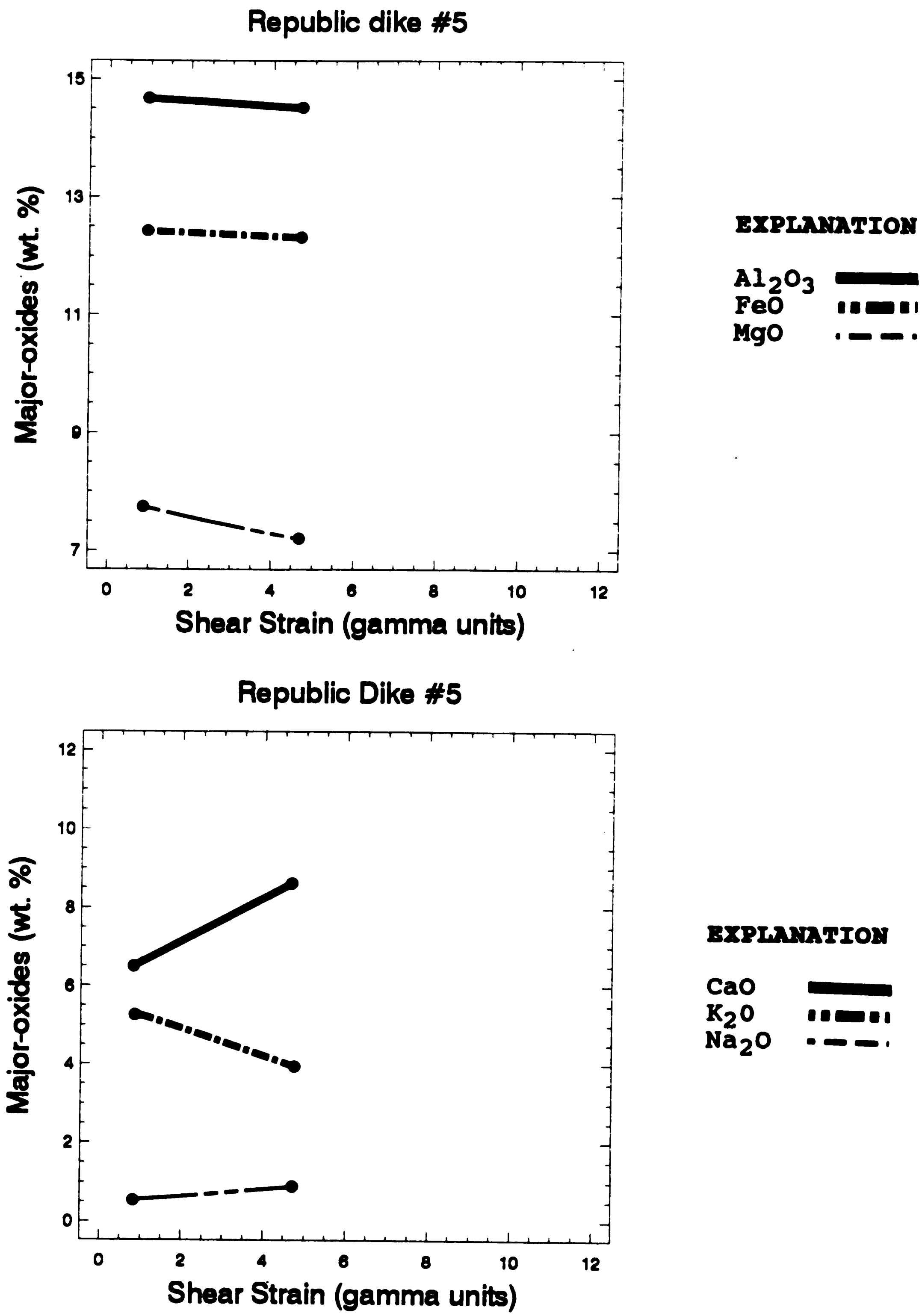


Figure 39.--Plot of major-oxides vs. shear strain, Republic dike 5.

DISCUSSION

Chemical and mineralogical changes accompanied the Penokean deformation of Lower Proterozoic diabase dikes in the Marquette-Republic region. Solution transfer of some chemical constituents appears to have accompanied Penokean shearing in several of the dikes studied. The largest contribution to this process appears to be calcium, although sodium depletion was also noted, and the mineral most affected by this process is plagioclase. The orientation of the dikes with respect to Penokean maximum principal stress (σ_1) appears to have controlled the extent of these changes (Myers, 1984).

Recent studies of shear zones by O'Hara (1990) and Glazner and Bartley (1991) have demonstrated the applicability of using bulk-rock chemical analyses to show volume loss in deformed zones, and provided the model used in this study.

It was anticipated that some or all of the foliated dikes sampled and measured near the Republic Trough would display chemical and mineralogical characteristics indicative of volume loss. The analyses of the Republic dikes, which intrude a felsic terrane, were combined with analyses of surrounding wall rock, and two dikes intruding an igneous terrane at Lighthouse Point. The wall rock and LHP dikes were analyzed primarily for comparison purposes.

The Republic area dikes were targeted as probable sites for analyzing deformation-induced volume loss, primarily on the basis of prominent sigmoidal foliation, and straight country rock contacts, indicating that the dikes were exposed to a single major episode of deformation, the Penokean tectonic event dated 1.89-1.82 Ga. (Hoffman, 1988).

Dike samples were analyzed petrographically. Original ophitic texture is nearly absent in all Republic dikes and it is assumed that all minerals present in the samples have been recrystallized. The Republic dikes sampled are all amphibolites, and the most abundant minerals are amphibole, biotite, and plagioclase. Deformation and additional recrystallization of individual grains is increasingly prevalent toward the dike margins (high-strain regimes). Dike margin samples are commonly comprised of needle-like mafic minerals oriented sub-parallel to foliation, with fresh felsic minerals, contained interstitially. Dike interior samples are commonly comprised of irregularly-shaped, non-oriented grains. Margin samples typically contain a higher modal percentage of mafic minerals (biotite, chlorite, amphibole, and opaques) than dike interior samples. The modal increase in mafic phases is often accompanied by a modal decrease in plagioclase and plagioclase alteration minerals, such as epidote, and a mineralogical change from highly-sericitic, twinned grains to untwinned grains with little alteration.

Bulk-rock chemistry was analyzed using X-ray fluorescence techniques. Major oxides and trace elements were analyzed and the results plotted against distance from dike margin to document chemical changes over the range of strain regimes. Depletion of major oxides and enrichment in conserved trace elements would indicate the possibility of volume loss. CaO depletion of 1-5 weight percent was noted in all dikes, except dike 5. CaO comprises a significant portion of the total bulk rock in these samples, and depletions of 1-5 weight percent are the largest noted among the major oxides, suggesting solution transfer of calcium from these dikes was probably the single largest contributor to volume change. Many-fold enrichments of conserved trace elements such as Ti and P, used as evidence of volume loss in other studies, are conspicuously absent in these dikes.

Shear strain measurements allowed an estimate of total displacement for Republic dikes 1, 2, and 5. Following methods of Ramsay (1967, 1980), shear strains were calculated for individual sampling locations, as well as the entire shear zone. The total shear strain is high, ranging from 4.6-13.9 γ units. Total extension measured along the principal strain axes (λ_1) ranges from 500-1400%. These strains are large, although Wood (1974) noted similar extensions in slate belts. Nonetheless, extensions of this magnitude may be justifiable however, as foliation is nearly asymptotic at the dike margins.

Select major oxides were also plotted against total shear strain. The results of these analyses were mixed. Dike 2 was the only dike with major-oxide depletion and trace-element enrichment trends similar to those noted in other volume loss studies. CaO was depleted in dike 1, but little variation in the other oxides accompanied increased strain. The chemical trends of dike 5 differ from those of other Republic area dikes, with large variations of select major oxides accompanying increasing strain, included enrichment in CaO. No strain data were available for dikes 3 and 4, although depletion of major oxides, particularly CaO and Na_2O, is shown in bulk-rock chemistry.

The Lighthouse Point dikes are oriented approximately orthogonal to Penokean principal stress (Myers, 1984), and were not sheared and no fabric is noted in either dike. LHP dikes have remnant igneous textures, and pyroxene comprises a significant modal percentage of the east-west trending dike. The LHP and Republic dikes are assumed to have been texturally similar before the Republic dikes were sheared. Depletion of less than one weight percent is noted for several major oxides, although little complementary enrichment is noted in the immobile trace elements.

This study did not investigate heterogeneity within the dikes, although there is some evidence to suggest that the dikes are at least locally heterogeneous, and any future study should consider this possibility. One Republic dike contains a large (approximately 20 cm) xenolith of granitic rock (Figure 6), and more contamination of this type is likely. Several specific locations were resampled, and chemical variations beyond the margin of error were noted for several of the major oxides. Additional sampling should include several samples from each strain regime, particularly the dike margins, which should be rigorously sampled along the length of the exposure.

In conclusion, chemical and mineralogical changes evident in several of the dikes can be interpreted as the result of volume loss, primarily the result of removal of Ca and Na from the system by alteration of Ca-rich plagioclase. The magnitude of the volume loss is unknown, although it may have been substantial in dikes 3 and 4. Analyses of the Lighthouse Point dikes indicate that little or no volume loss accompanied deformation of these dikes. Chemical and petrographic analyses for Dike 5 are puzzling, and could be interpreted as the result of positive volume change, rather than loss. The magnitude of strain measured in several of the dikes is great enough that volume change cannot fully account for the deformation observed in these dikes.

CONCLUSIONS

It is concluded that Penokean deformation of some foliated Lower Proteorzoic metadiabase dikes in the Marquette-Republic region of Upper Michigan was accompanied by volume loss, although much of the deformation appears to have occurred as a result of bulk-rock material transport. Other foliated dikes of similar age appear to have deformed without accompanying volume loss, as do dikes of similar age that are non-foliated because of their orientation to Penokean-age principal stress.

Volume loss appears to have occurred when calcium and sodium were removed from the system at some point during the alteration or recrystallization of Ca-rich plagioclase. Much of the plagioclase in high-strain regimes (dike margins) is Na-rich, untwinned, and interstitial, while most plagioclase in low-strain regimes (dike interiors) is Ca-rich, twinned, and highly sericitic. Although highly-altered, these interior grains are often subhedral-euhedral in shape, and some may be remnants of the original igneous textures.

Similar chemical trends are observed in most foliated dikes, small to moderate depletions of CaO, Na_2O, and Al_2O_3 in high-strain regimes, with little enrichment of typically conserved elements. Previous volume loss studies have noted much larger depletions of major elements, and enrichments in conserved major and trace elements which are conspicuously absent in these samples. Contamination of the dikes from K_2O-rich wall rock appears negligible, with possible exception of two Republic area dikes.

Sigmoidal foliation of the Republic area dikes was highly-visible in the field, with maximum shear strain at each dike margin, decreasing away from the margins. Shear strain measured in several Republic area dikes was very high, and the maximum extension in the measured dikes exceeds 1000%.

Much greater volume losses would be required to explain the strain measured in these dikes, than those measured during in this study.

REFERENCES

REFERENCES

Barker, A. J., 1989. Introduction to Metamorphic Textures and Microstructures. Chapman and Hall, New York. 162p.

Baxter, D. A. and Bornhorst, T. J., 1988. Multiple discrete mafic intrusions of Archean to Keweenawan Age, western Upper Peninsula, Michigan. Institute on Lake Superior Geology, Proceedings and Abstracts, v.34, p.6-8.

Becker, G. F., 1904. Experiments on schistosity and slaty cleavage. U.S. Geol. Surv. Bull., v.241, p.9-34.

Berger, A. R., 1971. Dynamic analysis using dikes with oblique internal foliations. Geol. Soc. Amer. Bull., v.82, p.781-786.

Best, M. G., 1982. Igneous and Metamorphic Petrology. W. H. Freeman and Company, New York, 630p.

BVTP, 1981. Basaltic volcanism on the terrestrial planets. (Lunar and Planetary Institute), Pergamon Press, New York.

Cambray, F. W., 1978. Plate tectonics as a model for the environment of deposition and deformation of the early Proterozoic (Precambrian X) of northern Michigan (abstr). Geol. Soc. Amer. Abstr. w/Programs, v.10, p.376.

Cambray, F. W., 1984. Proterozoic geology Lake Superior, S. shore, A field guide. Geological Association of Canada, 55p.

Cannon, W. F., 1973. The Penokean Orogeny in northern Michigan. Geological Association of Canada Special Paper 12, p.251-271.

Cannon, W. F. and Gair, J. E., 1970. A revision of stratigraphic nomenclature for Middle Precambrian rocks in northern Michigan. Geol. Soc. Am. Bull., v.81, p.2843-2846.

Cannon, W. F. and Simmons, G. C., 1973. Geology of part of the Southern Complex, Marquette District, Michigan. U.S. Geol. Surv. Jour. Res., v.1, p.165-172.

Cloos, E., 1947. Oolite deformation in the South Mountain Fold. Geol. Soc. Amer. Bull. v.58, p.843-918.

Fisher, O., 1884. On cleavage and distortion. Geol. Mag., Dec 3, v.1, p.268-276; 396-406.

Gair, J. E. and Thaden, R. E., 1968. Geology of the Marquette and Sands quadrangles, Marquette County, Michigan. U.S. Geol. Surv. Professional Paper 397, 77p.

Glazner, A. F. and Bartley, J. M., 1991. Volume loss, fluid flow and state of strain in extensional mylonites from the central Mojave Desert, California. Journal of Structural Geology, v.13, p.587-594.

Gresens, R. L., 1967. Composition-volume relationships of metasomatism. Chemical Geology, v.2, p.47-65.

Hoffman, P. F., 1988. United States of America, The birth of a craton: early Proterozoic assembly and growth of Laurentia. In: Wetherwill, G. W., Albee, A. L., and Stehli, F. G., eds., Annual Review of Earth and Planetary Sciences, v.16, p.543-604.

Huysken, Kristin, T., 1993. Chemical variation of the tephra fall beneath the Rainier mesa ash-flow sheet: implications for incremental growth of a large magma flow. M. S. Thesis, Michigan State University.

James, H. L., 1955. Zones of regional metamorphism in the Precambrian of northern Michigan. Geol. Soc. Amer. Bull., v.6, p.1455-1487.

Miller, W. J., 1945. Observations on pseudodikes and foliated dikes. Jour. Geol., v.87, p.175-190.

Mills, James, G., 1991. The Timber Mountain tuff, southwestern Nevada volcanic field: geochemistry, mineralogy and petrogenesis. v.1, Ph.D. Dissertation, Michigan State University.

Morey, G. B., 1973. Stratigraphic framework of Middle Precambrian rocks in Minnesota. In: Young, G. M., ed., Huronian stratigraphy and sedimentation. Geological Association of Canada Special Paper 12, p.211-249.

Myers, G. A., 1984. Structural analysis of foliated Proterozoic metadiabase dikes in the Marquette-Republic region of Northern Michigan. M. S. Thesis, Michigan State University.

O'Hara, K., 1990. State of strain in mylonites from the western Blue Ridge province, southern Appalachians: the role of volume loss. Journal of Structural Geology, v.12, p.419-430.

Peterman, Z. E., 1979. Geochronology and the Archean of the United States. Econ. Geol., v.74, p.1544-1562.

Peterman, Z. E., Zartman, R. E., and Sims, P. K., 1980. Tonalitic gneiss of early Archean age from northern Michigan. Geol. Soc. Amer. Special Paper 182, p.125-134.

Philpotts, A. R., 1989. Petrography of Igneous and Metamorphic Rocks, Prentice Hall, Englewood Cliffs, New Jersey, 178p.

Ramsay, J. G., 1967. Folding and Fracturing of Rocks, McGraw and Hill, New York, 568p.

Ramsay, J. G., 1980. Shear zone geometry: a review. Journal of Structural Geology, v.2, p.83-89.

Ramsay, J. G. and Graham, R. H., 1970. Strain variation in shear belts. Canadian Journal of Earth Sciences, v.7, p.786-813.

Ramsay, J. G. and Huber, M. I., 1983. The Techniques of Modern Structural Geology, Volume 1: Strain Analysis. Academic Press, New York, 307p.

Ramsay, J. G. and Wood, D. S., 1973. The geometric effects of volume change during deformation processes. Tectonophysics, v.16, p.263-277.

Russell, J. K., Nichcoll, J., Stanley, C. R., and Pearce, T., 1990. Pearce element ratios: A paradigm for the testing of petrologic hypotheses. EOS, v.71, p.234-235, 246,247.

Sims, P. K., 1976. Precambrian tectonics and mineral deposits, Lake Superior region. Econ. Geol., v.71, no.6, p.1092-1118.

Sims, P. K., Card, K. D., Morey, G. B., and Peterman, Z. E., 1980. The Great Lakes tectonic zone--A major crustal structure in central North America. Geol. Soc. Amer. Bull., v.91, p.690-698.

Sims, P. K. and Peterman, Z. E., 1983. Evolution of Penokean foldbelt, Lake Superior region, and its tectonic environment. Geol. Soc. of Amer. Special Paper 160, p.3-14.

Sorby, H. C., 1853. On the origin of slaty cleavage. Edindb. New Philos. J., v.55, p.137-148.

Sorby, H. C., 1908. On the application of quantitative methods to the study of rocks. Geol. Soc. Lond. Q. J., v.64, p.171-232.

Talbot, C. J., 1982. Obliquely foliated dikes as deformed incompetent single layers. Geol. Soc. Amer. Bull., v.93, p.450-460.

Van Hise, C. R. and Bayley, W. S., 1897. The Marquette iron-bearing district of Michigan. U.S. Geol. Surv. Mon. 28, 608p.

Van Hise, C. R. and Leith, C. K., 1911. Geology of the Lake Superior Region. U.S. Geol. Surv. Mon. 52, 641p.

Van Schmus, R. W., 1976. Early and middle Proterozoic history of the Great Lakes area, North America. Phil. Trans. R. Soc. Lond. A. v.280, p.605-628.

Van Schmus, R. W. and Woolsey, L. L., 1975. Rb-Sr Geochronolgy of the Republic area, Marquette County Michigan, Can. J. Earth Sci., v.12, p.1723-1733.

Westjohn, D. B., 1989. Regional finite strain patterns in proterozoic slates and quartzites: implications for heterogeneous strain related to flexural slip folding in the Marquette synclinorium. Ph.D. Dissertation, Michigan State University, 182p.

Wood, D. S., 1974. Current views on the development of slaty cleavage. Annual Review of Earth and Plan. Sci., v.2, p.368-401.

Wright, T. O. and Henderson, J. R., 1992. Volume loss during cleavage formation in the Meguma Group, Nova Scotia, Canada. Journal of Structural Geology, v.14, p.281-290.

Wright, T. O. and Platt, L. B., 1982. Pressure and cleavage in the Martinsburg shale. American Journal of Science, v.282, p.122-135.

APPENDICES

APPENDIX 1.--Results of XRF analysis of samples from Republic area dike 1.

OXIDE	Rep1-4 Dike Center	Rep1-3 0.27m from Margin	Rep1-2 0.13m from Margin	Rep1-1 Dike Margin	Rep1 Wall-Rock Margin	Rep1 Wall-Rock Interior
SiO2	49.94	49.20	50.87	49.62	79.13	75.88
Al2O3	14.60	14.62	14.24	14.77	11.79	13.87
FeO	11.69	11.72	11.78	11.78	1.01	1.87
MgO	7.42	7.44	7.45	7.44	0.55	0.62
CaO	9.27	8.43	7.88	7.76	0.90	0.24
Na2O	0.58	0.61	0.49	0.46	2.05	2.26
K2O	2.63	4.00	3.40	3.46	4.79	6.45
TiO2	1.20	1.22	1.26	1.26	0.09	0.26
P2O5	0.13	0.13	0.13	0.12	0.04	0.05
MnO	0.18	0.19	0.19	0.20	0.01	0.02
Total	97.64	97.56	97.69	96.87	100.36	100.52
TRACE ELEMENT						
Cr	198.1	234.7	244.3	172.7	0	7.1
Ni	113.9	169.4	125.2	125.0	11.1	4.8
Cu	68.7	54.2	6.4	5.2	19.3	12.6
Zn	129.9	126.4	104.5	107.4	14.8	24.7
Rb	181.2	201.1	262.1	317.9	137.3	162.8
Sr	147.0	148.7	113.0	94.4	129.1	64.1
Y	28.9	22.7	20.3	20.2	19.4	35.2
Zr	95.2	101.7	103.6	97.3	67.7	170.7
Nb	8.3	14.1	13.4	7.9	4.0	12.3
La	21.0	22.5	7.8	14.5	91.1	113.9
Ba	143.5	213.1	383.3	285.0	378.5	641.5

APPENDIX 2.--Results of XRF analysis of samples from Republic area dike 2.

OXIDE	Rep2 Dike Center	Rep2 Dike Margin	Rep2 Wall Rock Margin	Rep2 Wall Rock Interior
SiO2	46.67	46.72	72.81	75.88
Al2O3	13.81	13.56	13.78	13.87
FeO	10.29	12.23	2.10	1.87
MgO	12.44	11.91	1.53	0.62
CaO	7.93	7.26	0.92	0.24
Na2O	0.43	0.33	1.50	2.26
K2O	3.32	2.13	6.55	6.45
TiO2	0.75	0.84	0.28	0.26
P2O5	0.11	0.13	0	0.05
MnO	0.20	0.20	0.03	0.02
Total	95.95	95.31	99.50	100.52
TRACE ELEMENT				
Cr	820.4	4507.3	0	7.1
Ni	281.2	510.3	16.9	4.8
Cu	24.6	39.9	39.1	12.6
Zn	156.2	153.5	27.1	24.7
Rb	242.2	180.5	236.0	162.8
Sr	87.7	101.4	145.4	64.1
Y	11.1	21.1	14.3	35.2
Zr	58.8	65.0	202.6	170.7
Nb	13.6	20.3	14.3	12.3
La	85.2	77.3	151.9.	113.9
Ba	511.9	91.2	498.2	641.5

APPENDIX 3.--Results of XRF analysis of samples from Republic area dike 3.

OXIDE	Rep3-3 2.02m from Margin	Rep3-2 0.66m from Margin	Rep3-1 Dike Margin	Rep3 Wall Rock Margin	Rep3 Wall Rock Margin
SiO2	47.82	46.69	46.75	78.36	78.51
Al2O3	14.81	15.53	14.64	13.48	13.75
FeO	13.06	12.51	14.06	0.48	0.33
MgO	7.46	7.80	9.75	0.36	0.10
CaO	9.01	9.03	3.92	1.60	0.37
Na2O	1.55	1.72	1.05	3.86	7.19
K2O	1.78	1.53	4.85	2.33	0.73
TiO2	2.01	2.11	1.92	0.03	0
P2O5	0.25	0.27	0.25	0	0.01
MnO	0.20	0.20	0.18	0.01	0
Total	97.95	97.39	97.37	100.51	100.99
TRACE ELEMENT					
Cr	0	0	0	0	0
Ni	3.5	12.9	32.1	4.2	0
Cu	54.1	16.7	6.7	28.4	12.2
Zn	127.8	139.4	201.6	8.7	14.3
Rb	135.2	103.0	390.0	52.6	7.6
Sr	161.7	190.5	56.6	252.3	41.5
Y	26.6	21.1	25.3	4.8	18.8
Zr	113.1	123.4	104.4	81.3	97.5
Nb	25.4	16.8	26.3	17.1	105.9
La	46.5	75.6	13.9	35.3	77.6
Ba	343.2	230.3	1190.7	31.7	8.2

APPENDIX 4.--Results of XRF analysis of samples from Republic area dike 4.

OXIDE	Rep4-5 0.50m from Margin	Rep4-3 0.30m from Margin	Rep4-2 0.15m from Margin	Rep4-1 Dike Margin	Rep4 Wall-Rock Margin	Rep4 Wall-Rock Interior
SiO2	52.71	52.24	52.42	53.06	84.69	75.81
Al2O3	12.57	12.88	12.55	12.31	10.61	15.29
FeO	10.02	10.29	10.07	10.19	0.34	1.05
MgO	9.26	9.36	9.30	10.21	0.24	0.73
CaO	9.96	9.50	10.07	5.35	1.23	1.56
Na2O	2.00	1.98	2.07	1.66	3.61	5.58
K2O	0.84	1.28	0.82	3.20	1.55	1.86
TiO2	0.72	0.75	0.69	0.65	0.02	0.01
P2O5	0.07	0.07	0.06	0.06	0.03	0.02
MnO	0.18	0.18	0.18	0.15	0	0.01
Total	98.33	98.53	98.23	96.84	102.29	101.92
TRACE ELEMENT						
Cr	106.5	631.9	657.5	591.3	0	0
Ni	88.6	144.8	145.9	182.3	2.8	19.0
Cu	27.0	46.0	33.3	26.2	23.7	16.6
Zn	122.2	125.1	133.5	144.6	13.4	11.2
Rb	55.1	83.4	45.0	243.8	25.9	30.3
Sr	139.2	165.0	139.9	102.7	186.9	209.8
Y	14.7	12.7	15.0	17.6	0	62.0
Zr	60.4	60.0	49.7	62.6	35.3	56.0
Nb	5.6	9.6	11.8	0	0	0
La	39.8	2.1	20.0	45.1	60.5	76.9
Ba	21.0	149.2	26.5	488.0	124.1	249.7

APPENDIX 5.--Results of XRF analysis of samples from Republic area dike 5.

OXIDE	Rep5 Dike Center	Rep5 Dike Margin	Rep5 Wall Rock Margin	Rep 5 Wall Rock Interior
SiO2	48.26	48.53	75.03	75.75
Al2O3	14.67	14.50	13.93	12.50
FeO	12.38	12.28	1.38	1.21
MgO	7.75	7.24	0.56	0.37
CaO	6.61	8.59	1.55	0.69
Na2O	0.51	0.72	3.11	3.12
K2O	4.31	3.30	4.44	5.14
TiO2	2.04	1.97	0.17	0.17
P2O5	0.19	0.19	0.05	0.04
MnO	0.22	0.27	0.02	0.01
Total	96.94	97.59	100.24	99.00
TRACE ELEMENT				
Cr	294.5	282.7	0	0
Ni	120.1	128.3	9.3	9.9
Cu	18.4	15.6	25.6	21.5
Zn	245.7	229.7	18.4	31.1
Rb	395.3	271.3	157.5	203.4
Sr	79.3	81.9	154.8	73.5
Y	23.0	23.3	28.7	16.8
Zr	131.0	129.9	147.4	136.1
Nb	32.2	27.6	5.1	11.7
La	28.2	62.2	117.9	117.0
Ba	545.1	366.8	643.1	576.2

APPENDIX 6.--Results of XRF analysis of samples from east-west dike at Lighthouse Point.

OXIDE	LHP.E-W Dike Center	LHP E-W Dike Margin	LHP E-W Wall Rock Interior
SiO2	47.12	46.78	46.19
Al2O3	14.02	13.21	13.34
FeO	15.50	16.41	16.25
MgO	5.07	5.20	5.19
CaO	7.82	8.84	8.20
Na2O	2.53	1.98	2.11
K2O	0.76	0.79	1.32
TiO2	3.55	3.49	3.54
P2O5	0.48	0.55	0.53
MnO	0.26	0.28	0.27
Total	97.11	97.53	96.94
TRACE ELEMENT			
Cr	72.7	78.9	69.4
Ni	282.3	59.4	82.4
Cu	46.2	64.9	74.1
Zn	138.8	104.8	122.9
Rb	28.3	16.2	41.8
Sr	231.7	191.2	180.4
Y	36.2	47.4	39.9
Zr	236.0	231.5	229.1
Nb	25.3	11.2	18.3
La	89.0	59.3	78.8
Ba	375.6	302.3	461.5

APPENDIX 7.--Results of XRF analysis of samples from north-south dike at Lighthouse Point.

OXIDE	LHP N-S Dike Center	LHP N-S Dike Margin	LHP N-S Wall Rock Margin	LHP N-S Wall Rock Interior
SiO_2	47.77	46.46	52.09	46.63
Al_2O_3	13.34	13.75	15.01	17.01
FeO	7.67	9.41	11.48	12.15
MgO	10.04	10.06	4.05	3.54
CaO	9.19	8.25	8.82	10.65
Na_2O	3.28	2.99	2.59	2.64
K_2O	1.54	1.38	0.76	0.40
TiO_2	0.60	0.61	1.10	1.34
P_2O_5	0.42	0.44	0.11	0.12
MnO	0.15	0.17	0.26	0.27
Total	94.00	93.52	96.27	94.75
TRACE ELEMENT				
Cr	573.5	532.7	213.7	237.2
Ni	448.8	346.8	139.0	123.8
Cu	61.9	92.9	119.7	96.5
Zn	104.4	103.8	148.8	124.2
Rb	39.2	28.7	19.1	9.7
Sr	674.9	402.7	178.4	139.5
Y	13.0	11.5	19.8	26.1
Zr	146.2	141.2	77.6	86.5
Nb	0	0	0	3.0
La	122.7	128.9	16.7	40.9
Ba	942.0	889.5	303.2	133.6