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Mid-Proterozoic lamprophyre commingled with late-stage granitic dikes of the anorogenic San Isabel batholith, Wet Mountains, Colorado

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ABSTRACT

More than a dozen composite mafic-granitic dikes crop out along the northern margin of the San Isabel batholith, Wet Mountains, Colorado. The dikes crosscut and contain xenoliths of 1441 Ma granitic dikes and are in turn intruded by, but probably are coeval with, late-stage granitic dikes of the 1360 Ma San Isabel batholith. Only two other mafic representatives of the mid-Proterozoic anorogenic suite are known from Colorado. In the field, the dikes contain up to one-third granitic material by volume. Textures range from a swirling, lacy, mortarlike granite within basalt to subovoid pillows of basalt in granite. Many of the pillows contain small ovoids of the granite. The mutual inclusions and rounded to cuspate liquidlike contacts with minor mechanical mixing strongly indicate that these dikes formed through commingling of mafic and granitic liquids. The mafic dikes have the mineralogy and chemistry of lamprophyres, containing andesine, amphibole, biotite, sphene, and magnetite, with minor quartz and epidote and rare K-feldspar. Chemically, they average 52% SiO_2, and they are enriched in incompatible elements including the light rare earth elements. They are tholeiitic, compositionally similar to within-plate basalts with rift affinity. They partially mixed with the granite to produce intermediate-composition rock with 56% SiO_2. The granite is a monzogranite with biotite, hornblende, and sphene. Its mineralogy and chemistry are characteristic of the San Isabel batholith. The lamprophyres may be related to mantle-derived mafic liquids that were hypothesized to have melted lower crust to produce the San Isabel batholith. The lamprophyres may have migrated up around the margin of the batholith and mixed with late-stage granite to form these composite dikes.

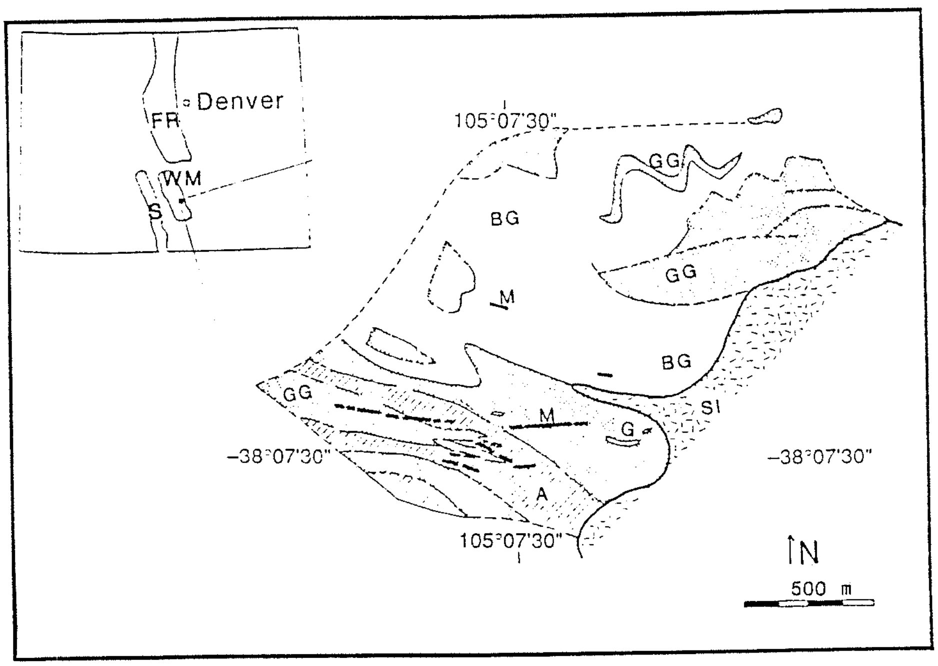

Figure 1. Location and geologic sketch map of South Hardscrabble Creek region of Wet Mountains. Inset of Colorado shows locations of Wet Mountains (WM) relative to Front Range (FR) and Sangre de Cristo Range (S). Map of study area shows occurrences of composite dikes along northern margin of San Isabel batholith (SI). Metamorphic units include amphibolite (A), granitic gneiss (GG), and biotite gneiss (BG). G indicates 1441 Ma granite sills. Heavy lines indicate composite mafic dikes (M), not to scale.

INTRODUCTION

Commingling of basaltic and granitic liquids in dike complexes has been observed in several localities (e.g., Nain complex, Labrador—Wiebe, 1980, 1987; Laramie anorthosite, Wyoming—Meurer and Lindsley, 1988). Mafic dikes, which crop out along the northern margin of the mid-Proterozoic San Isabel batholith in the Wet Mountains, have mixed with granitic liquid derived from the batholith to form composite dikes (Fig. 1).

Mafic dikes have been recognized previously in the Wet Mountains. However, they have usually been considered Phanerozoic in age. Some mafic dikes appear to be related to the lower Paleozoic Gem Park–McClure Mountain alkalic complexes (Parker and Sharp, 1970); others may be related to Tertiary lamprophyric dikes from the Spanish Peaks (Johnson, 1968). Many of these mafic dikes intrude Precambrian granitic dikes and are therefore demonstrably younger (Louden, 1988). However, all mafic dikes that do not contain the commingling textures described below have been eliminated from this study.

The composite dikes we are describing are part of the mid-Proterozoic anorogenic belt that crosses North America (e.g., Anderson, 1983). Mafic liquids are a minor but important component of this anorogenic belt. Very little of such mafic material has been recognized in Colorado, despite the occurrence of many anorogenic granitic batholiths in the mid-Proterozoic. For example, four large granitic plutons and several smaller stocks have been recognized in the Wet Mountains (Noblett et al., 1987). A mafic dike swarm in the northern Front Range near the Wyoming border includes one dike dated at 1350 Ma (K-Ar; Peterman et al., 1968), though no petrography, geochemistry, or genetic models were presented with that date. The Electra Lake gabbro in southwestern Colorado was dated at 1454 Ma (Bickford et al., 1969). Thus, the petrographic and geochemical data presented in this paper provide new information about the development of the anorogenic belt in Colorado.

GEOLOGIC SETTING

The composite dikes that we have located so far all crop out in an 8 km stretch along the northern margin of the San Isabel batholith near

GEOLOGY, v. 18, p. 120–123, February 1990

South Hardscrabble Creek in the Wet Mountains, Colorado. Amphibolite-grade metamorphic country rock hosts these dikes. The country rock comprises a 1700-m.y.-old terrane of biotite-gneiss metasedimentary rocks with lesser proportions of metabasaltic amphibolite and granitic gneiss that show geochemical signatures of modern back-arc basin tectonic settings (Noblett et al., 1987). Plutons of Silver Plume age, about 1400 Ma, occur throughout the Wet Mountains. The youngest of these batholiths is the weakly foliated San Isabel batholith (1360 Ma, U-Pb; Thomas et al., 1984). Unique aspects of this batholith include the presence of biotite, amphibole, and sphene; metaluminous chemistry; very low initial Sr ratio (0.7030); and weak foliation. These data led Cullers et al. (1987) to hypothesize a mantle melting event that in turn melted young crust (1800 Ma mantle separation age, Sm-Nd; DePaolo, 1981), previously depleted during the Boulder Creek intrusive episode, to generate the batholith. The mafic dikes of this study have commingled with granitic liquid apparently from the San Isabel batholith.

AGE OF INTRUSION

Two observations constrain the time of intrusion of the mafic dikes. First, the dikes crosscut, penetrate with small tongues, are chilled against, and in one place contain a xenolith of granitic dikes along South Hardscrabble Creek dated at 1441 Ma (U-Pb by M. E. Bickford; Noblett and Bickford, in prep.). Second, the mafic dikes are in turn intruded by small granitic dikes. In places, these latter bodies can be traced into the San Isabel batholith, therefore limiting the age of the mafic dikes to between 1360 and 1441 Ma. It seems unlikely that the granitic dikes are significantly younger than this, both because of their association with the margin of the batholith and because granitic bodies of younger age in this region of Colorado are unknown.

The field relations discussed below indicate commingling of mafic liquids with the granitic dikes. Thus, we believe that the mafic dikes are contemporaneous with the granitic dikes of the late-stage San Isabel batholith and, therefore, are dated at approximately 1360 Ma.

FIELD DESCRIPTION

The key feature that enabled us to distinguish the mafic dikes of this study from other unrelated mafic dikes along South Hardscrabble Creek was a lacy or mortarlike texture of granitic material that swirled within the mafic dikes (Fig. 2). The proportion of granitic and mafic material is highly variable not only between dikes, but also along strike within individual dikes. Where the mafic material dominates, small thumb-sized ovoids of the granite are enclosed within rounded pods of basalt up to about 0.3 m across, which are themselves enclosed by granite (Fig. 3). Isolated labradorite crystals in the granite and potassium feldspar crystals in the mafic material indicate that mixing has occurred in these dikes.

Where the composite dike is more than about one-third granite, the basalt formed as separate pods that range from about 10 cm to as much as 35 cm across. These pods closely resemble pillows, and we interpret them to be pillowlike chilling of basalt against granitic liquid. Similar pillow structures have been observed in mid-Proterozoic anorogenic complexes in both Labrador and Wyoming (Wiebe, 1980; Meurer and Lindsley, 1988). From these observations, particularly the mutual inclusions and rounded to cuspate contacts, we conclude that these are composite dikes composed of coexisting but only partially miscible granitic and mafic liquids.

PETROGRAPHY

Mineralogy

The mafic dikes contain about 40% calcic andesine, 25% blue-green pleochroic amphibole, 22% biotite, 5%–10% opaques (primarily magnetite), and 2%–8% sphene. Minor amounts of quartz (1%–2%) and trace amounts of epidote and, rarely, K-feldspar are present. Several relict clinopyroxenes are almost entirely altered to amphibole, sphene, and biotite. The rocks in thin section have a fine-grained, equigranular texture. Mineral forms vary from euhedral feldspars to splotchy anhedral amphibole and biotite crystals. On the basis of this mineralogy and the chemistry discussed below, the mafic dikes are best classified as spessartite lamprophyres (Rock, 1977).

The granitic part of the composite dikes contains variable proportions of quartz, microcline, perthite, and calcic oligoclase, with 5%–10% biotite and amphibole and magnetite and minor sphene and apatite. Myrmekite is common. The dikes are fine grained, allotriomorphic, and monzogranitic in composition.

Contact Relations

In thin section, the contact between the granite and lamprophyre is very sharp and rounded to cuspate, lacking any tonguelike injections of either material. A thin reaction boundary zone ranges from 0.05 to 0.5 mm in thickness. It is characterized by fine-grained anhedral quartz with minor biotite and dentritic opaques. The zone lacks both K-feldspar and plagioclase. Biotite and opaques extend into this zone from the lamprophyre, but they are sparser there than in the lamprophyre. In one thin section, flow-aligned biotites in the lamprophyre were partially deflected at the boundary.

Crystals of resorbed K-feldspar occur in the lamprophyre. One such crystal showed a Carlsbad twin between microcline and perthite, the edges of which had been completely converted to myrmekite. Within the granite, small clots of plagioclase and, in one case, an opaque mineral were overgrown by a necklace of K-feldspar and quartz.

Figure 2. Photograph showing swirling pattern of granitic material within mafic dike.

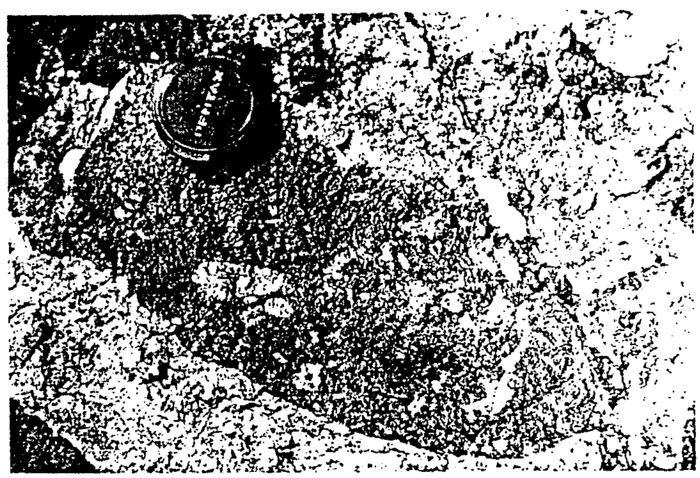

Figure 3. Commingling of mafic and granitic liquids produced this pattern of globs of granite within rounded basalt within granite.

Our observations indicate that minor mechanical mixing occurred between the mafic and granitic liquids and that a reaction zone composed largely of quartz developed between the two liquids. The curvature of the contact and mutual inclusions of resorbed material indicate that these were coexisting liquids; the well-defined sharp contact and deflection of flow-aligned biotite suggest that mechanical mixing was restricted. We found no conclusive evidence for textures such as statistically valid variations in plagioclase length or skeletal crystals that would suggest significant undercooling of the mafic liquid against the granitic liquid. Thus, the temperature difference at the contact between the two liquids was not very large; however, the viscosity contrast was sufficient to prevent extensive mixing.

PETROCHEMISTRY

Powders were prepared for eight samples of the lamprophyre, four samples of the lamprophyre near granite, and four samples of the granite. Fused disks were analyzed (by analytical chemist Nathan Bower) for major, minor, and ten trace elements (Rb to Nb) by X-ray fluorescence on an automated Rigaku spectrometer at Colorado College. U.S. Geological Survey standards were used to ensure accuracy of the tests. Powders from four lamprophyres (two of which were near the contact) and four granitic dikes were used to analyze the other trace elements by instrument neutron activation analysis at Nuclear Activation Services and Bondar Clegg. The lamprophyres are about 52% SiO_2; the granitic rocks are about 70% SiO_2, and the region near the contact has intermediate SiO_2 values of about 56% (Table 1). Despite minor alteration, the lamprophyres show remarkable chemical consistency on numerous mafic-discriminant diagrams. The lamprophyres plot in tholeiitic fields on eight different graphs—FeO vs. FeO/MgO, SiO_2 vs. Cr, Nb/Y vs. Zr/TiO_2, Jensen cation, SiO_2 vs. Nb/Y, FeO vs. MgO, Zr/P_2O_5 vs. Nb/Y, and $Na_2O + K_2O$ vs. SiO_2. They are also light rare earth element (REE) enriched with a small positive Eu anomaly. On a spider plot (Fig. 4), they are strongly enriched in large ion lithophile–incompatible elements relative to mid-oceanic ridge basalt (MORB). K, Zr, La, and Nb are significantly higher than in MORB. Ba, Rb, Zr, P, and Y are also high.

The intermediate parts of the dikes plot as andesites on various classification diagrams. They show slightly lower Fe, Mg, and Ca and higher Na than do the lamprophyres. This chemical variation is not apparent in petrographic analysis.

The granite analyses show K higher than Na and have high Fe/(Fe + Mg) ratios. They plot near the low-pressure granite minima trough. They are enriched in light REE and show no Eu anomaly. On a spider plot they show a tight pattern enriched in the more incompatible elements. They are subalkalic and metaluminous to marginally peraluminous; alumina numbers are between 1.01 and 1.07.

TABLE 1. AVERAGE CHEMICAL ANALYSES OF LAMPROPHYRIC, INTERMEDIATE, AND GRANITIC PARTS OF COMPOSITE DIKES, WET MOUNTAINS, COLORADO

	Mafic 8 Samples	Intermediate 4 Samples	Granite 4 Samples
Oxides (wt.%)			
SiO_2	52.4	55.8	72.60
TiO_2	2.06	1.80	0.24
Al_2O_3	14.3	14.3	14.01
Fe_2O_3	11.9	10.8	1.60
MnO	0.18	0.15	0.03
MgO	4.5	3.7	0.36
CaO	7.1	6.5	1.29
Na_2O	2.9	3.1	3.60
K_2O	2.05	2.1	4.30
P_2O_5	0.99	0.77	0.08
Total	98.38	99.02	98.11
Elements (ppm)			
Rb	63	55	180
Sr	783	779	335
Y	55	44	24
Zr	368	323	266
Ni	48	64	(15)
Co	27	21	(4)
Cr	117	124	(1)
V	217	199	19
Zn	130	120	44
Nb	27	19	16
La	93.5	62.2	103
Ce	180	121	205
Nd	85	57	-
Sm	14.6	9.9	7.1
Eu	4.57	3.43	2
Tb	1.8	1.3	1
Yb	5.32	3.88	(5)
Lu	0.77	0.56	(0.5)
Ag	(2)	(2)	(5)
Au	(5)	(5)	(5)
Ba	1540	1300	775
Hf	8.4	6.3	9
Mo	1	3	(2)
Sb	2	0.1	(0.2)
Sc	27.6	23.4	4.9
Ta	1.0	0.7	2
Th	2.3	2.7	44
U	1.1	1.1	9.7
W	2	1	2

Note: Major and minor elements and 10 trace elements (Rb to Nb) were analyzed by neutron activation. Numbers in parentheses are analyses below detection limits.

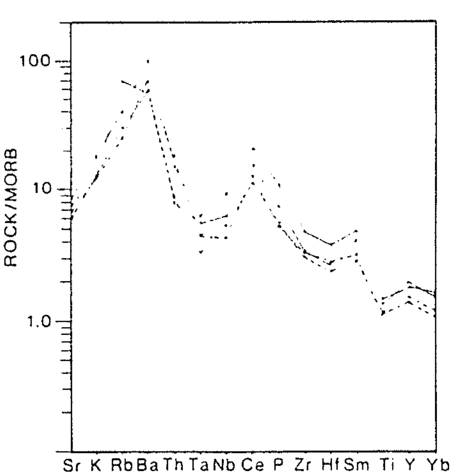

Figure 4. Spider plot of incompatible elements for two mafic dikes (solid lines) and two intermediate parts of mafic dikes (dashed lines), normalized to MORB.

ORIGIN OF THE DIKES

Lamprophyre

To evaluate a possible tectonic setting for the lamprophyres, we plotted the chemical data on a large number of discriminant diagrams relevant to mafic liquids. The dikes all show rift affinity on those diagrams that separate volcanic arc from rift basalts (Ti vs. Cr, Ti/Cr vs. Ni, Nb vs. Ta, and Th vs. Ta). The dikes all plot in the fields for continental or calc-alkalic basalt on diagrams that discriminate between oceanic arcs and continental arcs (Ti/Zr vs. Zr/Y, Th/Hf, and Ta/Yb vs. Th/Yb). They all plot in the within-plate fields (Fig. 5) on diagrams that include a field for within-plate basalts (TiO_2 vs. Zr, Sr/Ce vs. Sr/Nb, and Nb vs. Zr vs. Y). The spider plot (Fig. 4) showed that these dikes were not MORB and were highly enriched in incompatible elements relative to island-arc tholeiites. They are chemically similar to both calc-alkalic basalts and within-plate basalts. Thus, they seem to fit best in a nonsubduction continental setting possibly involving rifting. Their occurrence in the North American anorogenic belt is appropriate for this setting.

Intermediate

Using a modified version of IGPET, we modeled the intermediate compositions, assuming a linear mixing model for the major elements and 13 trace elements. We had two sets of samples in which the granitic, intermediate, and mafic material occurred within a single dike, and we also modeled the average values of the three compositions. All three trials produced similar results. A mixture of approximately 13% granite and 87% mafic liquid produces the intermediate composition for these elements within the limits of analytical error. Of the 39 elements in Table 1, only La, Ce, and Hf do not fit this model. Limited magma mixing during commingling of the mafic and granitic liquids best explains the occurrence and composition of the intermediate rocks.

Granite

A spider plot for the granite dikes shows that they do not resemble primitive arc granite but are most similar to modern mature arc granite in regions with well-developed continental crust. These dikes plot at the border between arc and within-plate settings on granitic discriminant diagrams (Rb vs. Yb + Ta, Rb vs. Y + Nb, and Rb/10 vs. Hf vs. Ta × 3). Like the lamprophyres, the granites appear to have intruded in a region of thick continental crust, possibly in a within-plate regime.

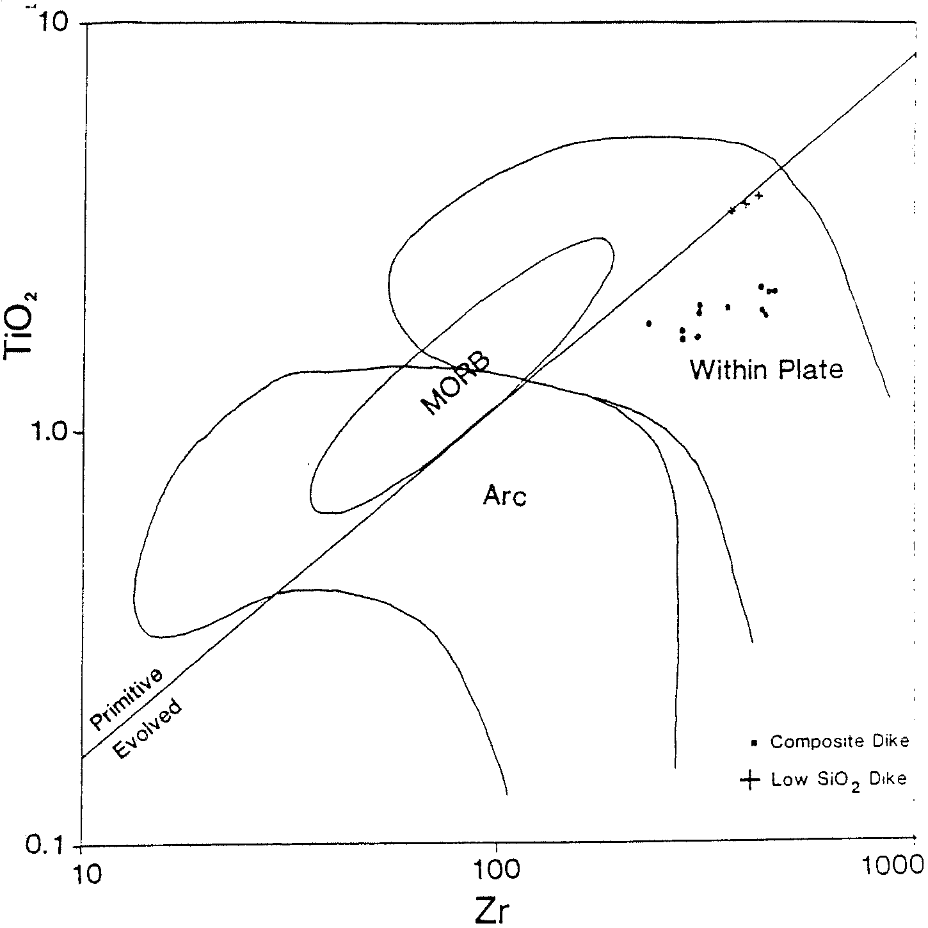

Figure 5. TiO_2 vs. Zr discriminant diagram showing within-plate rather than arc or MORB tectonic setting for these dikes (diagram from Pearce et al., 1981).

Six mid-Proterozoic granitic plutons have been recognized to have been emplaced in the Wet Mountains. The granitic dikes of this study occur at the margin of the San Isabel batholith. The San Isabel batholith is unique among the Wet Mountain granitic rocks because it is the least differentiated and most metaluminous (ranging to peraluminous), and the only one containing amphibole and biotite with sphene. It ranges in composition from quartz monzonite to monzogranite.

The granites of this study also contain both biotite and hornblende with minor sphene, though in lesser percentages than those of the average San Isabel granitic rocks. They lack the typical Eu anomaly, but otherwise are chemically similar. These similarities in mineralogy and chemistry, as well as the occurrence of the dikes at the margin of the San Isabel batholith, indicate that these dikes are late-stage San Isabel material.

DISCUSSION

If Cullers et al. (1987) were correct in hypothesizing that a mantle melt provided the heat to generate the San Isabel batholith, then the lamprophyres are probably related to that mantle melt. They are contemporaneous with the granitic liquid and are concentrated along the edge of the batholith. Perhaps the mafic liquid was unable to rise directly through a more viscous granitic magma and was channeled to the edges of the magma chamber.

These considerations would restrict the mafic dikes to have formed after a well-defined viscous magma chamber had developed. The compositions of the dikes might reflect not the original mantle melt that produced the San Isabel magma itself, but a somewhat younger mafic liquid that had commingled with late-stage granite. The mafic liquid has a strong signature on tectonic discriminant plots of a continental, within-plate setting.

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ACKNOWLEDGMENTS

We thank Bob Weibe, Bob Cullers, and Steve Box for helpful reviews and Deborah Ferguson for her secretarial services.

Manuscript received May 31, 1989
Revised manuscript received August 25, 1989
Manuscript accepted September 8, 1989