DIKES OF THE NORTHEAST ADIRONDACK REGION - INTRODUCTION TO THEIR DISTRIBUTION, ORIENTATION, MINERALOGY, CHRONOLOGY, MAGNETISM, CHEMISTRY, AND MYSTERY

Y.W. ISACHSEN and W.M. KELLY
New York State Geological Survey

C. SINTON and R.A. COISH
Middlebury College

M. T. HEIZLER
SUNY Albany

INTRODUCTION AND SCOPE

More than 1300 dikes in the Adirondack region have been compiled on a map at 1:250,000 (Isachsen and Wright, in press). Figure 1 is a severe reduction of this map. While 1300 may seem a large number of dikes, the sparsity of rock exposures in the region suggests that it represents at most a few percent of the total number actually present. Most dikes are exposed over a length of only a few meters or less, and are a meter or so thick. Several, however, are exposed intermittently for distances up to 15 km, and are as much as 10 m thick. Twenty-four types are represented, five of which are metamorphic. Mafic dikes clearly predominate. Their prominence, in decreasing order, using the names given in the literature, are as follows: diabase, "mafic dike", basalt, gabbro, metagabbro, metadiabase, hyperthene metadiabase, and garnet metadiabase. Next most prominent are lamprophyres and granite pegmatite dikes. Rose diagrams of dike orientations (Isachsen and Wright, in press) show these dominant strike directions: 1) NNE-NE for the basalt, diabase, gabbro and "mafic" dikes, 2) WNW to EW for the lamprophyres, and 3) NS to NNW for the metamorphic dikes. The northeasterly strikes of most of the unmetamorphosed mafic dikes corresponds to the predominant trend of faults and zero-displacement crackle zones that account for the great number of linear valleys in the southeastern half of the Adirondacks (Isachsen and McKendree, 1977; Isachsen and others, 1983). The easterly-westerly trends of the lamprophyre dikes correspond to the trends of similar dikes in Vermont (McHone and Corneille, 1980, McHone, 1984). Their radiometric dates are similar as well.

This trip will include two stops to see lamprophyre dikes and one to see the most impressive concentration of dikes in the Adirondacks - the Rand Hill dike swarm. Here, more than 100 dikes, up to 180 m in exposure length, are exposed in three cross-cutting orientations. Diabase, olivine diabase, and trachyte porphyry dikes intrude gabbroic anorthosite gneiss.

Subjects for discussion will include: dike orientations vs regional fracture patterns, magnitude of extensional strain, dike propagation mechanisms, relative and radiometric ages (and problems), paleomagnetism and apparent polar wander path, geochemical

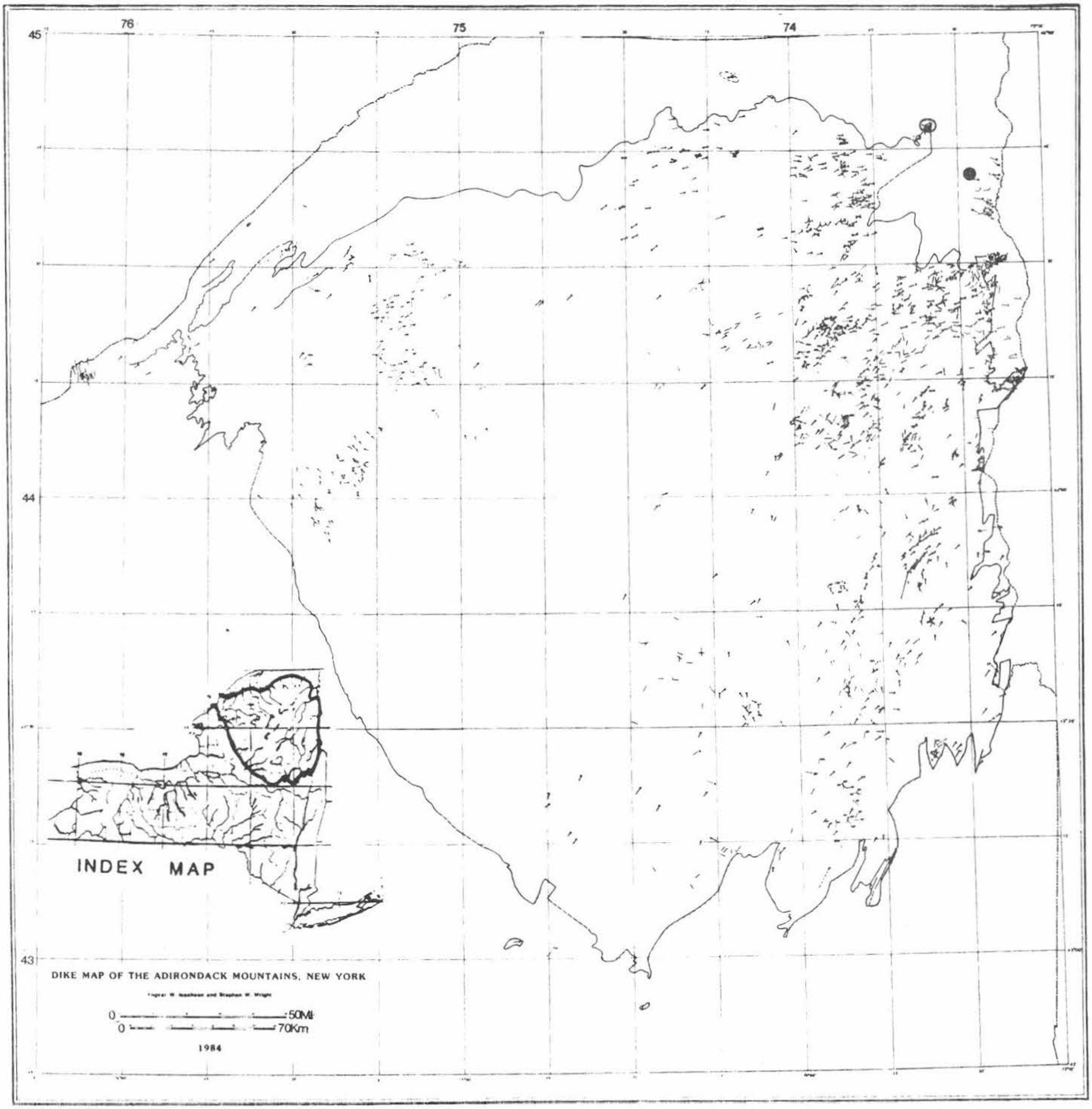


Figure 1. Dike map of the Adirondacks showing the distribution and attitudes of dikes in the region (reduced from Isachsen and Wright, in press, 1:250,000). Twenty-four types, five of them metamorphic, are differentiated on the original large scale map. Multiple dikes with similar orientations at many sites increase the number beyond those shown here. Dikes are concentrated in the eastern Adirondacks and the Thousand Islands region, the general paucity of dikes in between is probably real (Isachsen & Wright, in press). Plattsburgh is shown by solid circle, Rand Hill by open circle.

characterization, and plate tectonic inferences.

Authorship contributions are as follows: Geochronology, M.T.H. and Y.W.I.; petrography, W.M.K., Y.W.I., C.W.S.; paleomagnetism, W.M.K.; geochemistry, C.W.S., R.A.C.; stop descriptions, Y.W.I., C.W.S. We are very grateful to David Seidemann for K/Ar dating, James Olmsted for helpful conversations, Shirley Pytlak for petrographic information on the Rand Hill dikes, Robert Barry for Figure 11, and to Mr. McKinney and Dr. John Mazur for their cordial cooperation in allowing field studies on their respective properties. We are most grateful for helpful reviews by J.G. McHone, J.F. Olmsted, W.B. Rogers, and P.R. Whitney.

GEOCHRONOLOGY

A major goal of compiling a map of Adirondack dikes (Isachsen and Wright, in press) was to determine the history of paleostress in the region through K-Ar dating of dikes of known orientation. Making the simplest assumptions, dikes will intrude perpendicular to the axis of least principal horizontal stress, and parallel to the axis of maximum principal stress. A successful study would show the changes in stress orientation through whatever time interval was represented by the dikes, and thus elucidate the regional tectonic history of the northeastern part of North America (Isachsen and Seidemann, 1983). Conventional K-Ar analyses were made by Seidemann on 24 whole rock samples from unmetamorphosed dikes including diabase, olivine diabase, trachyte, and lamprophyres. Five lamprophyre dates ranged from 146 to 123 Ma and one trachyte porphyry intruded into Paleozoic strata gave a date of 113 Ma (Isachsen and Wright, in press). Spanning the Late Jurassic to Middle Cretaceous period, these ages indicate an easterly-westerly maximum principal stress at that time. This agrees with trends and dates reported by McHone and Corneille (1980) and McHone (1984) for trachyte dikes cutting Ordovician strata along the Vermont shores of Lake Champlain. They obtained an Rb/Sr isochron for several dikes of 125 ± 5 Ma.

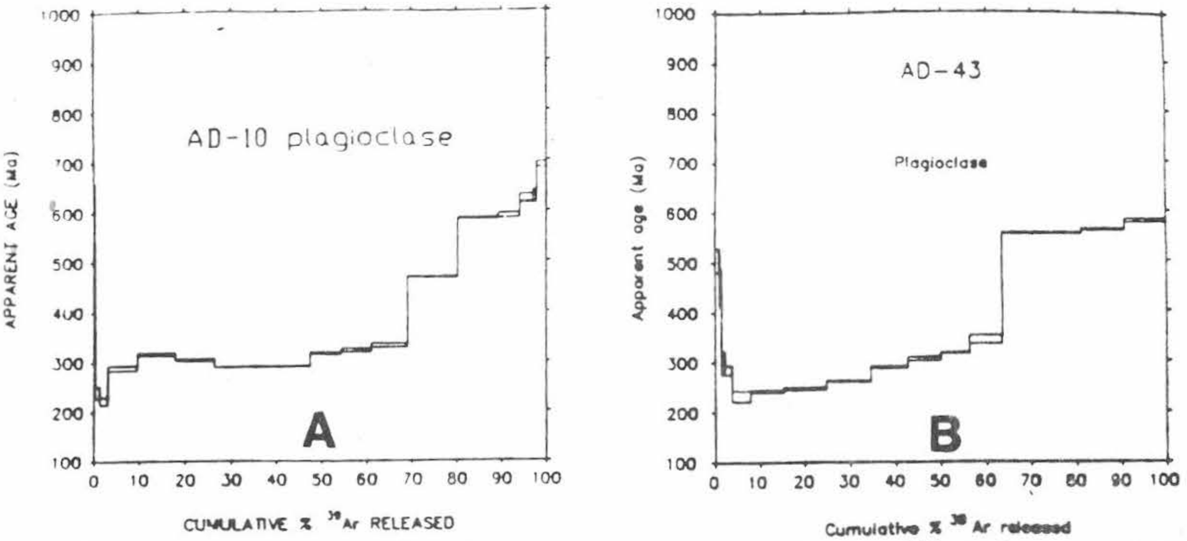
The K/Ar dates for diabase and olivine diabase in the eastern Adirondacks show a wide range (Geraghty and Isachsen, 1979; Isachsen and Wright, in press). Seven dates at Rand Hill cluster in the comparatively narrow range 588-542 Ma. Progressing southward, however, ages become younger, reaching 261 Ma at Pottersville which is located 140 km south of Rand Hill. This is consistent with the younging of K-feldspars along this same trend (Heizler and Harrison, 1987). With respect to the Rand Hill dikes, it is interesting to note that diabase dikes with the same ENE trend and "Iapetan age" occur in the Ottawa graben, where Bourne and Hogarth (1978) report K/Ar dates of 564-570 Ma.

The younger diabase dikes in the south central and southern Adirondacks, however, are surprising because no diabase dikes have yet been found that cut rocks younger than the Middle Proterozoic basement. Kemp and Marsters (1893) and Cushing (1898) early noted that diabase dikes did not cut the basal Paleozoic Potsdam Sandstone of Middle Cambrian age. The pre-Potsdam age of such dikes is further confirmed by Cushing's discovery of glacial boulders of Potsdam sandstone containing pebbles of diabase. Cushing also found trachyte porphyry fragments in such boulders. This demonstrates the existence of a pre-Potsdam intrusive episode of trachyte in addition to that of Mesozoic age referred to above. Also, there is field evidence that the diabase and trachyte porphyry dikes at Rand Hill are coeval: Cushing (1901) describes a diabase dike that cuts a trachyte porphyry dike, while at another site (about 300 m southwest of the map area in Fig. 11), Geraghty and others (1979) document the reverse intrusive relationships. This suggests that if these trachytes are of the same generation, the Rand Hill dike swarm is a bimodal comagmatic suite. This conclusion receives support in the section on Geochemistry, although more dikes in the Rand Hill swarm should be dated and analyzed to test this possibility.

The ambiguity between the relative and K/Ar ages of diabase dikes in the southeastern Adirondacks inspired the use of the $^{40}Ar/^{39}Ar$ method to some of the K-Ar dated dikes. Before discussing the results, it is desireable to give a brief review of the $^{40}Ar/^{39}Ar$ method because of its bearing on the interpretation of the data obtained.

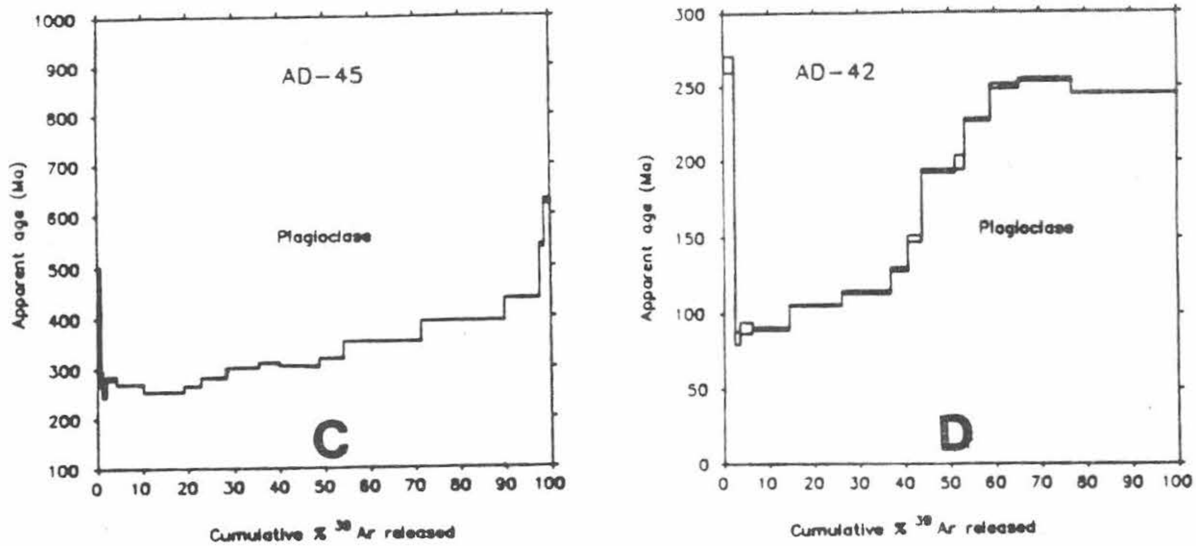
True crystallization age can be determined only if there has been neither a gain nor loss of ^{40}Ar, either during or after emplacement. Such an assumption, however, can be hazardous. Argon, being an inert gas, can diffuse <u>into</u> dike minerals from K-rich country rock or incorporated xenoliths during intrusion. Alternatively, it can readily diffuse <u>out of</u> minerals during even relatively small temperature perturbations if they are persistent on geological time scales (i.e. millions of years). Thus, for example, argon will diffuse out of plagioclase at temperatures between 100-200°C and cause an anomalously young K-Ar age. An additional problem is that plagioclase generally contains ^{40}Ar in <u>excess</u> of that produced from <u>in situ</u> decay of ^{40}K. Such argon contamination will result in a K-Ar date <u>older</u> than the crystallization age. Nevertheless, conventional K-Ar dates can only be based on the assumption that all the non-atmospheric ^{40}Ar was produced by <u>in situ</u> decay of ^{40}K.

To test this assumption, an $^{40}Ar/^{39}Ar$ incremental heating technique can be used. Briefly, this requires irradiation of the sample whereby ^{39}K is transmuted to ^{39}Ar through a neutron-proton reaction. Inasmuch as ^{39}Ar is proportional to ^{40}K, and is thus a measure of the parent concentration in the material, the $^{40}Ar/^{39}Ar$ ratio (essentially the daughter-to-parent ratio) will be proportional to age. Heating the sample in a series of increasing temperature steps and plotting the percentage of ^{39}Ar evolved at each step versus its calculated age creates an age spectrum (Fig. 2). If the sample has undergone neither argon loss nor gain, each incremental release of gas should yield the same age, resulting in a flat spectrum or "plateau". Deviations from a plateau will generally indicate a gain, loss, or both of ^{40}Ar during the geological history of a sample. Such release spectra can provide dates that are far more geologically significant than those obtained through conventional K-Ar dating. For a complete description of the $^{40}Ar/^{39}Ar$ method <u>and</u> the interpretation of release spectra see McDougall and Harrison (1988).



Fort Ann dike, north of Fort Ann on Rt. 22.

Pottersville dike, Pottersville entrance ramp to I-87.



The Glen dike, quarry ~2 km south of The Glen.

Big Nose dike, Rt. 5, ~12 km west of Fonda.

Figure 2. ^{40}Ar/^{39}Ar release spectra for plagioclase separates from three diabase dikes located within a 40 km radius in the southeastern Adirondacks, 140 km south of Rand Hill, and one (Big Nose) from the southernmost Adirondacks. The age gradients suggest post-crystallization argon loss. A. Sample yields a plateau from 3 percent to 70 percent of the ^{39}AR released, with an age of ~300 Ma. This may be a cooling age following Paleozoic burial. The last 35 percent released may reflect the ~600 Ma crystallization age of the dike, excess ^{40}Ar, or a combination of the two. B. Age spectrum shows excess ^{40}Ar over the initial ~5 percent of gas released, with a minimum at ~233 Ma. The age gradient for the first ~63 percent of gas released is indicative of argon loss. The unusual dramatic age increase at ~63 percent may reflect a relatively retentive siting for the argon then being released. The final 580 Ma age may be a minimum date of intrusion. A conventional K/Ar whole rock analysis gave a date of 261 ± 5 Ma (Isachsen and Wright, in press). C. Age spectrum shows an overall increase in age from early release until ~97 percent release. The age gradient probably reflects the ^{40}Ar concentration distribution that resulted from later reheating following emplacement prior to 450 Ma. The final gas release appears to be excess ^{40}Ar. A conventional K/Ar determination gave a date of 370 ± 7 Ma (Isachsen and Wright, in press). D. The young apparent ages of ~80 Ma reflect cooling below 100°C of this relatively low-retentive plagioclase. The very steep gradient probably results from excess ^{40}Ar, an interpretation strengthened by the age decrease for final gas release. If not caused by excess argon, the release spectra may indicate a minimum crystallization age of 250 Ma. A K/Ar determination gave a date of 377 ± 8 (Isachsen and Wright, in press).

Figure 2 shows release spectra for plagioclase from three dikes that are located from 120 to 140 km south of Rand Hill (Fig. 1). The apparent ages are variable, with all spectra displaying apparent age gradients rather than true-age plateaus. These age gradients reflect ^{40}Ar concentration gradients within the plagioclase crystals that result from both excess argon and argon loss, and thus probably do not yield dike crystallization ages.

The age spectra for plagioclase samples from the diabase dikes shown in Fig. 2 lack broad plateaus, and, aside from the Pottersville dike, even the oldest ages are younger than the age bracketed by field relationships. Conventional K-Ar ages on these samples would therefore be meaningless geologically.

The timing and cause of the apparent argon loss is a question of interest. Dalrymple and Lamphere (1969) have reviewed seven geological factors that can potentially cause argon loss in minerals: 1) the inability of the mineral lattice to retain argon, 2) melting, 3) metamorphism, 4) weathering and alteration, 5) recrystallization, 6) reheating, and 7) physical damage. In this connection, all thin sections of Adirondack dikes examined thus far show moderate to extensive alteration. Whether this alteration is deuteric or a later hydrothermal effect is not known, but the absence of hydrothermal alteration in associated country rocks suggests the former. Regardless of this question, a number of studies other than $^{40}Ar/^{39}Ar$ bear on the cause of argon loss.

As reviewed by Johnnson (1986) and Friedman (1987), seven independent indicators have shown that temperatures approaching 175°-200°C are recorded in the Middle and Upper Devonian strata of New York -- strata that Rickard's (1988) isopach maps suggest originally extended across the Adirondack region. The thermometers used are vitrinite reflectance, conodont coloration, distinctive authigenic minerals, reset fission track ages in apatites and zircons, fluid inclusion homogenization, stable isotopes of oxygen, and stable isotopes of carbon. Assuming that these elevated temperatures resulted from burial rather than igneous activity, 4 km of post-Upper Devonian sediments must have once covered the area (e.g. Johnnson, 1986), burying the basement to 8-9 km. This implies that the Carboniferous strata of Pennsylvania once extended northward across New York State. Reheating to 200°C by burial would cause argon loss in the plagioclase of diabase dikes and explain the Phanerozoic K/Ar ages.

$^{40}Ar/^{39}Ar$ studies by Heizler and Harrison (1987) suggest that the time of this reheating and subsequent uplift and cooling to below 150°C was about 180 Ma ago (Early to Middle Jurassic). They proposed another cause of reheating, namely, burial during the Devonian coupled with influx of heat from an inferred failed rift to the east related to the opening of the Proto-Atlantic, (Iapetus).

PETROGRAPHY OF THE RAND HILL DIKES

Introduction

The petrography of dikes at Rand Hill is treated in some detail in this separate section because of its application to the next section, Paleomagnetism. The petrography of the other dikes is discussed under the appropriate field trip stop descriptions.

Three types of dikes occur at Rand Hill: diabase, olivine diabase, and trachyte porphyry. These will be examined at STOP 2 in both fresh roadcuts and an extensive area of natural exposures. Although some of the dike rocks are very fine-grained, they are classified as diabase rather than basalt, following the convention for hypabyssal versus extrusive rocks.

Diabases

As applies to basaltic rocks in general (e.g. Hatch and others, 1973) both diabase varieties at Rand Hill contain plagioclase and clinopyroxene as essential minerals, as well as abundant oxides of iron and titanium oxides. In addition to clinopyroxene, a calcium-poor pyroxene, either pigeonite or orthopyroxene, may also be present depending on temperature of crystallization. Plagioclase commonly appears in two sizes and generations: as early-formed phenocrysts and as more sodic microlites in the groundmass. Similarly pyroxene may be present in two generations. Hornblende is rare, but small amounts of biotite are not uncommon. Apatite, in small acicular crystals, is plentiful. As to the presence or absence of olivine, Hatch and others (1973) note that it occurs in most, though not all basalts and diabases, and is present either because (1) the magma is undersaturated in silica or (2) if slightly oversaturated, because early-formed olivine is prevented from converting to orthopyroxene by rapid chilling of the magma. In Adirondack olivine basalts and diabases, the olivine may be found in all stages of alteration to serpentine, talc, iddingsite, chlorite, magnetite, limonite, rhombohedral carbonate. Pyroxene may be replaced by chlorite, calcite, epidote.

In conjunction with a paleomagnetic study of the dike rocks at Rand Hill, a number of thin and polished sections were examined in transmitted and reflected light. The observations are given below.

Diabase. The samples examined were taken from sites RH-17 and RH-24 of Geraghty and others (1979), which correspond to samples collected by W. Kelly and L. Brown for a paleomagnetic study reported on by Brown (1982). Plagioclase, which makes up about 60 percent of the rock, forms laths and anhedral crystals that range up to 1.5 mm in length and average 0.1-0.5 mm. The laths are fairly strongly zoned and flow-aligned, and show 10-20 percent alteration. Biotite, generally in anhedral crystals, appears to be primary, and makes up 10-15 percent of the rock. It ranges from extremely fine-grained to 0.1 mm in diameter, and is abundant in the 0.01 mm size range. Intergrown with it is a secondary fine-grained greenish phase, possibly chlorite. Apatite needles, 0.05 mm in length, are abundant. Epidote, defined in the broad sense, occurs in amounts up to 10 percent and is probably a replacement of plagioclase. It is anhedral and averages 0.1 mm in size. Secondary calcite forms in rhombohedral grains 0.1 mm in diameter.

Opaque minerals make up approximately 15 percent of the rock. These, as in all the Rand Hill dikes, are dominantly iron-titanium oxides. Titanomagnetite has a bimodal grain size distribution. Subhedral grains, 0.02-0.04 mm with an observed maximum of 0.1 mm, display subsolidus oxidation exsolution textures as shown by the presence of ilmenite lamellae on the {111} planes of the magnetite (Haggerty, 1976). Homogeneous anhedral magnetite, 0.01-0.001 mm, is ubiquitous. An oxide dust, <0.001mm, is present in the silicates. It is probably magnetite but is too fine for definite identification with an optical microscope. Traces of pyrite, 0.025-0.05 mm, are present, and some contain minor patches oxidized to magnetite.

It is noteworthy, and will be referred to in the section on Geochronology, that both silicates and oxides are altered in the dikes, although silicates are the more altered.

<u>Olivine diabase</u> (porphyritic). This rock displays a range of textures that are related to the degree of alteration of the rock and the presence or absence of olivine or pyroxene phenocrysts -- minerals that weather to form pits. The mafic phenocrysts are concentrated in the central part of the dikes by flow differentiation. In contrast, the less dense plagioclase phenocrysts are more abundant near the margins. The samples examined were collected from sites RH-16, RH-20, RH-22 and RH-23 of Geraghty and others (1979). The following summarizes the characteristics of this entire suite of samples.

Plagioclase laths are present as phenocrysts, 1-5 mm long, in a groundmass of finer-grained laths 0.01-0.05 mm in length. The plagioclase phenocrysts commonly occur in rafts as though they stuck together during flow. The core of the plagioclase is tan, probably due to submicroscopic inclusions, and fades towards the rim. All the plagioclase is fairly strongly zoned. It constitutes 40-65 percent of the rock, and is 5-10 percent altered to sericite. Clinopyroxene occurs between the plagioclase laths in typical ophitic fashion, with a grain size of about 0.05 mm. A few highly-altered phenocrysts measuring 0.1-0.2 mm were observed. Clinopyroxene now forms only 1-3 percent of the rock whereas before its alteration to epidote, serpentine and clinozoisite, it made up about 40 percent in some samples.

Moderately to severely altered grains of olivine, 0.1-0.2mm in size are present in most samples. Where olivine is absent, its ghosts remain as clots of alteration products. These comprise oxides plus serpentine, with or without a brown alteration phase which is probably iddingsite. Only trace amounts of olivine remain, although originally it formed several percent of the rock. The relict alteration clots are rimmed, corona-like structures. Their core is a cloud of magnetite, hematite and pyrite which appears massive in thin section, but in polished section is revealed to be composed of many very small grains. The core is generally surrounded by a thin (<0.1 mm) discontinuous rim of a very fine grained colorless phase. This is rimmed by a green phase, probably serpentine, which is itself rimmed by or mixed with a fine-grained brown alteration product that contains small biotite crystals. The brown phase probably is iddingsite that overgrew biotite in the matrix as the alteration rim formed. It is the selective weathering of these alteration clots that accounts for the pitted surface of these dikes.

Biotite, in 0.25-1.0 mm anhedral to subhedral grains, is disseminated throughout the groundmass. It occurs both as primary grains and as secondary grains in alteration rims on FeMg silicates, and in aggregates of grains that seem to be derived from totally altered FeMg silicates. It forms up to 10% of the rock. Apatite needles have the same size range as in the diabase dikes, but are less abundant.

Epidote and serpentine are very common alteration minerals in these rocks. Epidote, in anhedral to subhedral 0.01 mm crystals, is disseminated in the matrix and also occurs in aggregates 0.3 mm across. These clots of epidote contain no relict mineral core but may be altered clinopryoxene. Epidote also occurs in the alteration rims of the silicates that form the weathered pits. The serpentine generally has a fibrous habit, radial to the edges of the altered FeMg silicate. Serpentine also occurs as veinlets. Epidote and serpentine together form as much as 30 percent of the rock. Opaque minerals make up 10-20 percent of the rock. These are distributed evenly through the matrix and are concentrated in the cores of the coronal structures. Although the most common opaque mineral is FeTi oxide, there is a wide variation in the degree of alteration of the oxides. Magnetite occurs both as a homogeneous phase and with included lamellae of ilmenite. Some grains are considerably altered to maghemite or hematite. In samples with altered oxides, completely altered grains may coexist in close proximity to unaltered grains.

Magnetite occurs as skeletal to subhedral 0.001-0.2 grains, both homogeneous and with exsolved ilmenite on {111} of the magnetite. Maghemite, formed as a late, patchy alteration product, may replace 50-100 percent of some grains. A very fine grained (<<0.001 mm) dusting of an oxide mineral, possibly magnetite, occurs in what appears in reflected light to be plagioclase.

Anhedral homogeneous magnetite occurs as clusters or clouds of 0.01 mm grains in the core of the rimmed aggregates that represent altered phenocrysts of olivine or pyroxene. These oxides are obviously secondary, formed from the breakdown of the silicate phase. A lesser amount of secondary acicular hematite is commonly associated with the magnetite in these clusters.

Late pyrite occurs as anhedral and locally euhedral grains 0.01-0.1 mm, both in the matrix of the rock and in the cores of the coronal structures that contain FeTi oxides. Pyrite makes up less than 1 percent of the opaques. A trace of chalcopyrite was also observed in the oxide clusters.

Trachyte. A general description of the Rand Hill trachytes by Cushing (1901) is summarized under STOP 2A. The following details are from specific samples of Rand Hill trachyte collected at station RH-21 of Geraghty and others (1979).

Plagioclase, which occurs as 0.1-0.2 mm laths with abundant very fine alteration products, constitutes approximately 25 percent of the rock. Potassium feldspar forms laths and anhedral crystals in the same size range, and was distinguished from plagioclase by staining. It makes up about 35 percent of the rock.

Fresh biotite, in subhedral, 0.01-0.1 mm grains, constitutes roughly 25 percent of the rock, and highly-altered clinopyroxene comprises about one percent. Apatite occurs as abundant needles, 0.05 mm and finer in size.

Opaque minerals make up about 15 percent of the trachyte. Anhedral magnetite is the most common, occurring with a bimodal grain size distribution. The larger grains, averaging 0.05 mm, are either homogeneous or display ilmenite lamellae on the {111} planes. These grains show up to 25 percent alteration to hematite, and perhaps 10 percent alteration to maghemite. The smaller grains, 0.01 mm and finer, are homogeneous, with only a minor amount of hematite alteration. Overall, the primary magnetite is 10-20 percent replaced by later minerals.

Minor discrete hematite grains, 0.05 mm and finer, appear anhedral and homogeneous. These lack any internal relict structure and so are probably secondary. In thin section, bright red hematite flakes were noted. Very minor pyrite forms 0.05-0.001 mm anhedral grains.

PALEOMAGNETISM OF THE RAND HILL DIKES

One hundred two oriented samples were collected from 20 sites among the Rand Hill dikes to establish paleomagnetic poles to accompany the K/Ar dates (Late Proterozoic, Lower and Middle Cambrian and Lower and Middle Devonian) published by Geraghty and others (1979). Natural remanent magnetization direction shows a strong preference for the earth's present magnetic field (Fig. 3). There is a fairly strong viscous component to the magnetization which may be due to secondary mineralization or to alteration of the primary magnetic phases. This component decreases in intensity fairly rapidly upon thermal demagnetization, reaching 20-30 percent of original intensity at 500^0C. After alternating-field demagnetization up to 50 mT, the direction moved to a more easterly declination, although the inclination remained steep. The mean direction for 17 dikes is $I = 64.4^o$ and $D = 63.4^o$ (alpha-95 = 7.5^o) (Fig. 4). This corresponds to a geomagnetic pole at 46.8^o N latitude and 351.2^o E longitude, which is far removed from Paleozoic poles for North America and is not similar to any younger poles for the continent (Fig. 5). Instead, the Rand Hill pole corresponds fairly well to some Precambrian poles (Brown, 1982).

The apparent polar wander (APW) path for Proterozoic rocks is not firmly established but paths have been suggested which share many

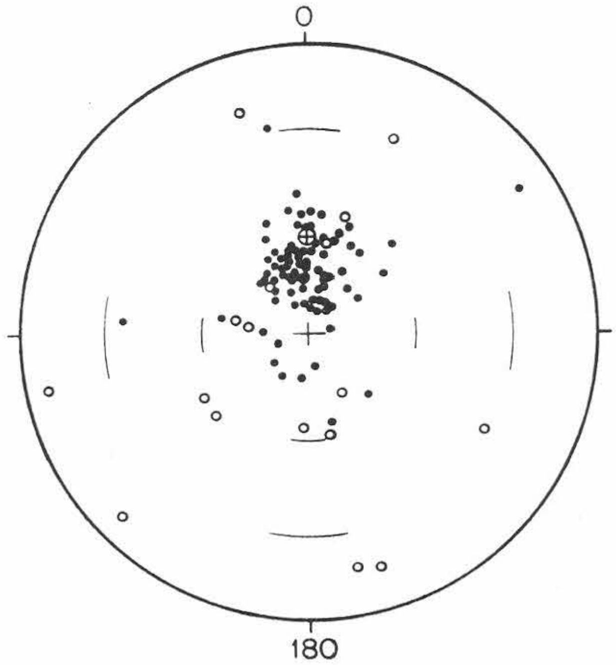


Figure 3. Natural remanent magnetization directions for all Rand Hill samples (n=102). Present earth field is indicated by cross in circle. Solid circle indicates positive inclination, open circle negative inclination.

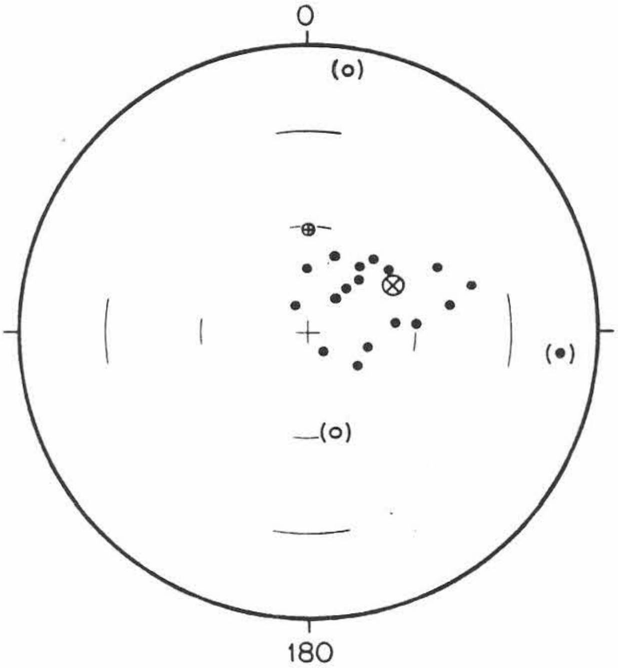


Figure 4. Inclination and declination of all Rand Hill sites. The mean is indicated by circled "x". Sites in parentheses are not included in the mean. The present earth field is shown by circled cross.

features. Figure 6 shows the position of the Rand Hill pole in relation to Grenville poles for North America. The correspondence is not exact but does suggest that the dikes may be older than the Paleozoic dates would indicate. Grenville paleopoles and part of the North American polar wonder path of Buchan et al. (1983) are shown in Figure 7. The Rand Hill pole falls at a point on this APW path which is pre-980 Ma in age. Given that the dikes are not metamorphosed, their maximum age is constrained by the Grenville event which affected the Adirondack rocks 1.0-1.1by ago.

Another APW path, (Roy and Robertson, 1978) is shown in Figure 8. The Late Proterozoic (Hadrynian) track in this figure is uncalibrated except for age limits between 950 Ma and 650 Ma from equator to equator. The Rand Hill pole falls on this track near the younger end but clearly before the 650 Ma position.

As was discussed under Geochronology, the K/Ar dates are now considered minimum dates of crystallization. Inasmuch as the dikes are relatively fine-grained and in places have glassy chill borders, they are interpreted to be Late Late Proterozoic or earliest Paleozoic, although this would be younger than the age suggested by the APW path proposed by Roy and Robertson above. In any case, the $^{40}Ar/^{39}Ar$ release spectra and the fact that the oxide phases, as well as the silicates, are altered, leaves further refinement of the diabase dike ages to the future.

GEOCHEMISTRY

Analytical methods

Four major and trace element analyses of dike rocks from Stop 1, and 15 from Stop 2, were made using an argon-plasma spectrometer at Middlebury College (Table 1). Neutron activation analysis of one sample was made for rare earth elements (REE) by Nuclear Activation Services, Ltd. in Ontario.

Results

The results show that although some of the major elements may have been mobile during alteration, all of the rocks have SiO_2 contents within the range of basalts.

Major and trace elements. All of the samples contain relatively high amounts of TiO_2 (2.32-2.65 percent). The differences among the three older dike types can be seen by plotting P_2O_5 vs. TiO_2, Sc vs TiO_2, and Ni vs FeO/MgO (Figs. 9a, 9b, 9c). In figures 9d and 9e, geochemical properties are plotted on tectonic diagrams. The Ti-Zr-Y diagram (Fig 9d) of Pearce and Cann (1973), shows that the diabase-olivine diabase dikes all fall in the center of the continental (within plate) basalt field, and the coarse-grained diabase (fine-grained gabbro) lies along its border. This classification fits the regional setting of these dikes. In the $FeO-MgO-Al_2O_3$ tectonic diagram (Fig. 9e) of Pearce and others (1977), the coarse-grained diabase again plots along the border of the continental basalt field. However, the diabase-olivine diabase

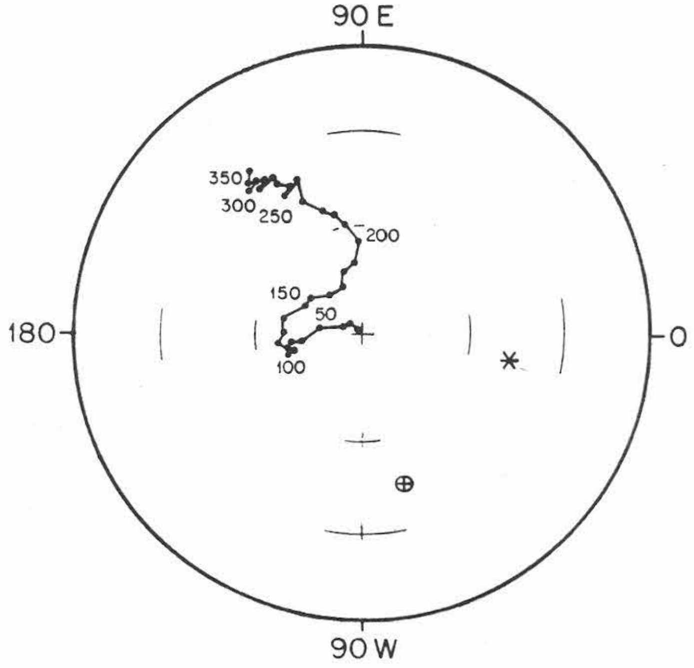


Figure 5. Apparent geomagnetic paleopole positions for the period 350 Ma to present. Center of diagram = north geographic pole. Star = pole position indicated by mean inclination and declination for Rand Hill. Circled cross = present position (latitude - longitude) of Rand Hill.

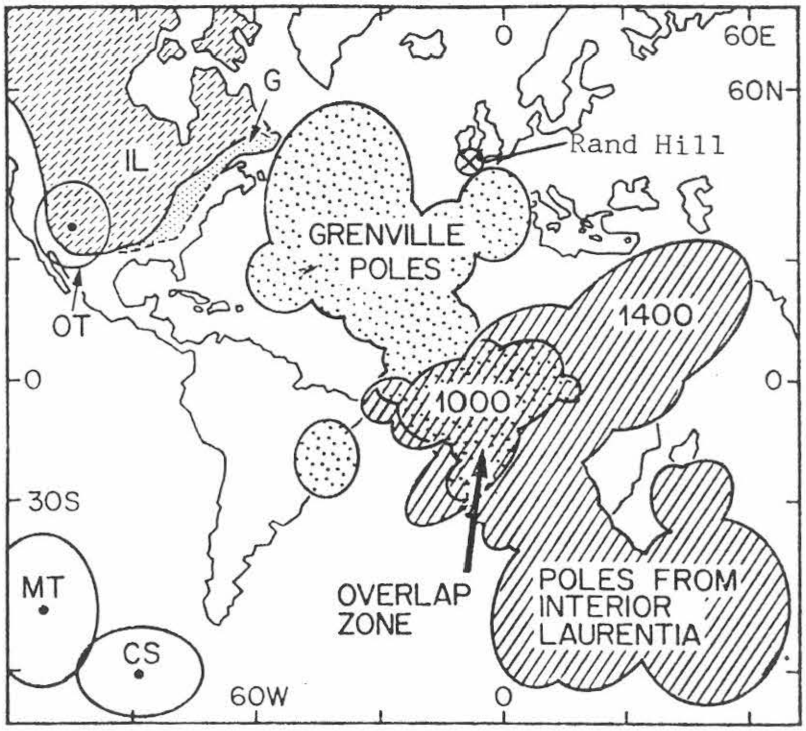


Figure 6. Rand Hill paleopole shown relative to Grenville paleopoles and others of the Grenville Structural Province. Modified from Irving and McGlynn (1976).

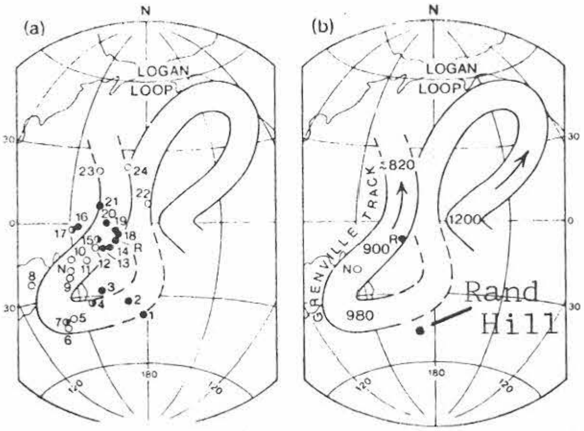


Figure 7. Grenville paleopoles and part of the APW path for North America (Buchan and others, 1983).

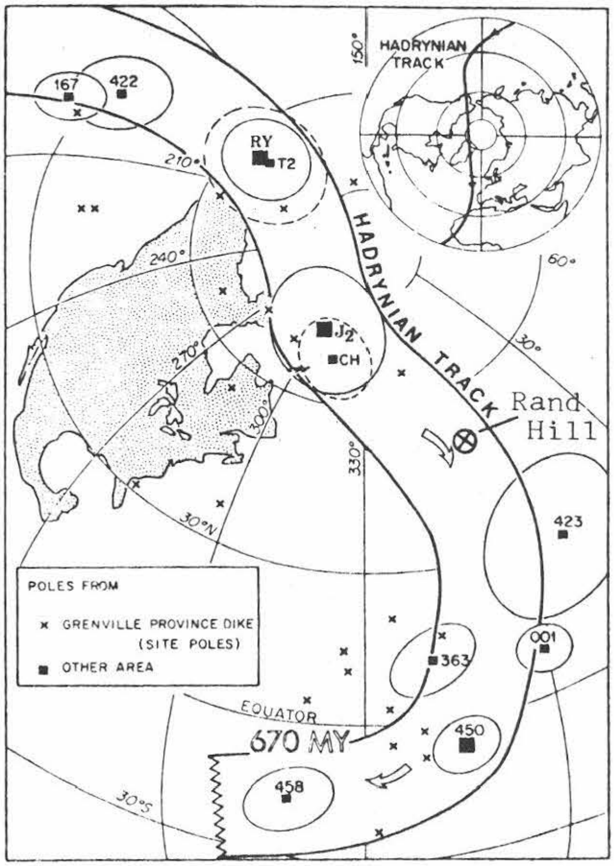


Figure 8. Part of the APW path for the Late Proterozoic, from Roy and Robertson (1978). Rand Hill paleopole is shown by circled "x".

Table 1

	Lamprophyres				Diabase ± Olivine								Coarse Diabase		Trachyte Porphyry				
Sample	6257	6258	6282	6283	6189	6190	6191	6193	6196	6198	6200	6201	6194	6197	6183	6184	6185	6186	6187
SiO_2	49.36	44.07	42.67	42.48	47.33	49.84	49.76	51.07	52.19	50.16	49.48	50.06	48.79	48.71	51.33	49.29	50.78	52.63	51.75
TiO_2	2.17	2.42	2.73	2.74	2.66	2.49	2.58	2.46	2.35	2.64	2.65	2.52	2.36	2.32	2.60	2.64	2.48	2.45	2.49
Al_2O_3	11.25	13.26	12.99	12.91	15.05	14.70	15.09	13.48	13.67	13.75	12.21	15.26	14.23	14.01	15.76	15.72	16.08	16.18	15.79
FeO	13.07	13.12	12.64	12.85	13.87	12.39	12.52	11.82	11.73	11.75	11.63	11.83	12.87	13.89	12.60	12.06	11.70	11.53	11.76
MnO	0.19	0.17	0.18	0.16	0.11	0.19	0.22	0.20	0.19	0.15	0.15	0.15	0.19	0.19	0.15	0.14	0.13	0.13	0.13
MgO	9.55	8.60	9.31	9.34	9.83	6.95	7.00	9.01	6.89	7.67	7.89	5.81	6.09	5.97	4.12	4.08	3.82	3.65	3.74
CaO	11.32	12.44	12.82	13.22	3.46	5.85	6.22	7.89	6.67	7.87	8.43	7.78	7.72	8.33	4.64	4.85	4.79	4.67	4.50
Na_2O	1.79	2.74	2.23	2.63	3.20	3.65	3.66	3.07	3.24	3.43	3.20	3.96	2.70	2.36	4.66	4.59	4.81	4.81	4.84
K_2O	2.15	1.97	2.28	2.28	1.78	1.65	1.86	1.43	1.44	1.55	1.45	1.69	1.52	1.79	2.84	3.06	3.40	3.45	3.31
P_2O_5	0.85	1.01	1.10	1.14	0.84	0.89	0.91	0.54	0.47	0.61	0.62	0.88	0.45	0.42	1.36	1.35	1.27	1.27	1.28
Total	101.70	99.80	98.95	99.75	98.13	98.60	99.82	100.97	98.84	99.58	97.71	99.94	96.92	97.99	100.06	97.78	99.26	100.77	99.59
LOI	9.10	5.80	4.67	4.64	4.94	2.36	2.33	2.33	2.99	2.16	1.85	1.84	2.00	1.67	2.11	1.70	1.52	1.54	1.68
Trace Elements (ppm)																			
Sc	23	23	25	24	21	18	17	22	23	21	22	18	33	32	12	12	13	11	12
V	202	229	270	266	211	179	179	197	189	206	186	179	275	276	96	102	93	88	87
Cr	191	191	169	158	220	148	141	335	217	233	304	141	168	129	23	10	29	7	19
Co	75	89	101	112	100	89	95	94	82	89	88	83	100	92	72	73	72	75	91
Ni	184	157	169	176	173	121	114	234	144	173	193	112	90	82	39	32	25	39	31
Sr	879	1121	2016	1630	390	570	537	422	334	488	526	706	238	226	620	652	647	658	593
Y	26	29	35	35	25	29	29	26	28	27	28	29	37	40	34	37	41	39	39
Zr	168	195	203	207	213	222	230	161	160	188	234	230	190	188	47	44	44	63	56
Ba	800	943	1393	1631	455	497	496	373	329	429	419	477	319	294	769	762	793	850	789

samples span the continental and adjacent ocean island fields. This is probably because any samples collected near the center of these flow-differentiated dikes would contain an above-average concentration of olivine and this would move the plots towards the MgFe side of the triangle. The trachyte porphyry samples fall outside of the tectonic fields of Pearce and Cann (1973) in Fig. 9d, but lie on the boundary of the continental basalt field in Fig. 9e. As discussed under Geochronology, field relationships suggest that the diabase and trachyte dikes are a coeval. Their geochemistry supports the interpretation that they are derived from a common magma source.

Rare-earth elements. The one sample of olivine diabase (sample no. 1968) that was analyzed for rare earth elements shows strong enrichment in the light rare-earth elements (LREE) relative to the heavy rare-earth elements (HREE) (Fig. 9f). This is similar to patterns found in early rift basalts in the Green Mountains (Coish and others, 1986) and in the Hudson Highlands (Ratcliffe, 1987). Modern alkali basalt from the African Rift system and oceanic islands have similar patterns.

The plots of Fig. 9e suggest that the olivine diabase and trachyte porphyry are geochemically similar to within-plate intrusions. This supports the interpretation that they are part of the rift-related volcanism along the eastern coast of North America that preceded the opening of the Proto-Atlantic (Iapetan) basin (e.g. Rankin, 1976). The diabases are similar to other basaltic rocks found along the Appalachians that are rich in Ti, Zr, Y, and P, and enriched in LREE.

The olivine diabases are chemically similar to the metadiabase dikes of the Hudson Highlands (Ratcliffe, 1987) and the Bakersville dikes of North Carolina (Goldberg and others, 1986) which cut Grenville-age basement along the western edge of the Appalachians and have been subjected to Taconian metamorphism. The chemically-similar dikes in the eastern Adirondacks are probably of the same vintage, but because the Adirondacks are part of the craton rather than the foldbelt, they are unmetamorphosed. The above metadiabase dikes have been interpreted as being associated with extension accompanying Iapetan rifting of North America, and the same interpretation fits the Adirondack diabases based on their relative age, geochemistry, and paleomagnetism.

Greenstones of the Tibbet Hill Formation in Vermont were interpreted by Coish and others (1986) as transitional to alkalic basaltic rocks that have high TiO_2, P_2O_5, Zr, and Y contents and are strongly enriched in the LREE relative HREE. Although the olivine diabases of Rand Hill have slightly lower Ti content and higher LREE. This may be because the Rand Hill dikes intruded the crust during earlier stages of Iapetan rifting (Coish and Sinton, 1988).

The geochemistry of lamprophyre dikes is described under Stop 1.

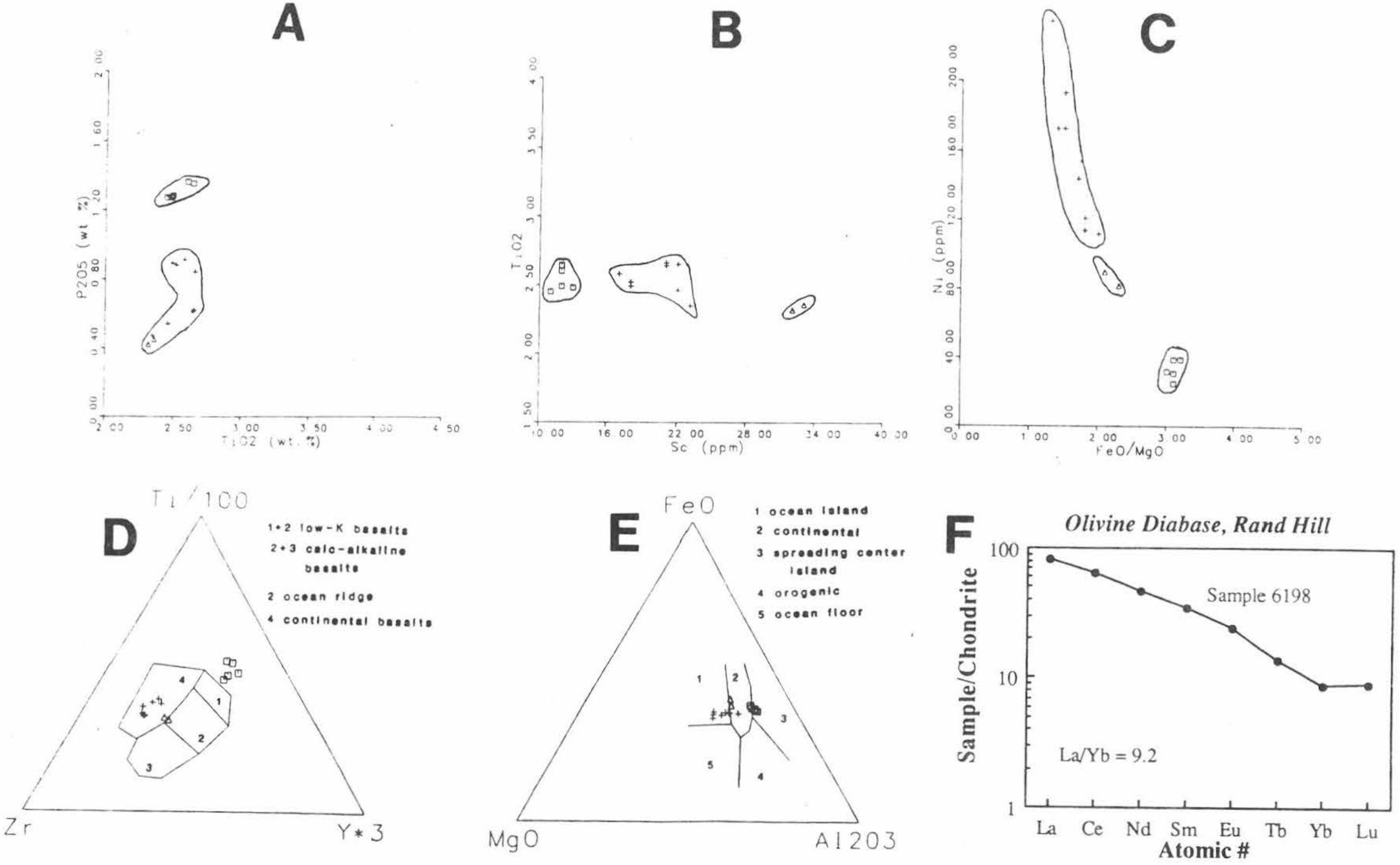


Figure 9. Geochemical plots showing the separate compositional fields of the three dike types: diabase-olivine diabase (plus sign), coarse-grained diabase (triangle), and trachyte porphyry (square). Triangular diagrams show tectonic fields proposed in the literature, as discussed in the text, and 9f shows rare earth element plot for olivine diabase sample 6198.

ROAD LOG

> "For the structural geologist, eroded dykes may be viewed as the remnants of full-scale tests of the fracture strength of the Earths crust. If field observations are properly interpreted, they will provide important constraints on the process of dyke emplacement."
>
> David Pollard, 1987

MILEAGE		
BETWEEN POINTS	CUMU-LATIVE	ROUTE DESCRIPTION
0	0	From parking lot at west end of Hudson Hall at SUNY-Plattsburgh, turn right onto Broad St. and head west.
0.3	0.3	Turn right (north) onto N. Prospect St.
0.7	1.0	Tom Miller Rd. Turn left (west) cross overpass over I-87.
0.3	1.3	Quarry Rd. Turn right (north). Pass Plattsburgh Quarries on left.
0.9	2.2	Intersection with NYS Rts. 374 and 22. Turn left (west) onto 374, get into right lane, and park.
0.2	2.4	**STOP 1.** LAMPROPHYRE DIKES

Two lamprophyre dikes cutting a tilted fault block of Crown Point Limestone (Middle Ordovician) of the Chazy Group. The dikes strike N65-73W and dip 83-85 NE, parallel to the prominent joint set here. They are about 50 cm thick and display chilled margins. They contain calcite amygdules, clinopypoxene phenocrysts and local xenoliths of gabbroic metanorthosite. The subject of lamprophyres has recently been reviewed by Rock (1987). The name covers a number of alkalic rock types that form dikes or sills, and rarely lavas. They are defined by their content of abundant euhedral to subhedral phenocrysts of mafic minerals such as olivine, amphibole, biotite, clinopyroxene, apatite or oxides, but not felsic phenocrysts; the groundmass may be mafic, felsic or glassy. Silica content and Na/K ratio vary widely.

In the field, lamprophyres may be difficult to distinguish from diabase dikes, but a careful examination of textures shows lamprophyres to lack the familiar ophitic or diabasic texture with its visible laths of plagioclase. Instead, lamprophyres have a pronounced panidiomorphic-granular (sugary) texture with mafic phenocrysts of various sizes in a fine-grained alkali groundmass. Spherical, calcite-bearing amygdules are common. They, and mafic phenocrysts, may weather preferentially to produce a pitted weathering surface. Although similar weathering also characterizes olivine diabase and olivine basalt, these show the lath-shaped crystals of plagioclase, commonly of phenocryst size.

The dikes at this locality are rich in amygdules filled with calcite. One dike shows an equigranular texture of biotite, plagioclase laths, subhedral and skeletal opaques, and olivine micro-phenocrysts, with some apatite and amphibole. Two samples taken from the southern side of the road show a characteristic porphyritic, texture, with large euhedral to subhedral phenocrysts of zoned clinopyroxene. The groundmass consists of essential biotite, plagioclase, subhedral opaques, apatite, and possibly amphibole. Alteration of the rock is minimal, but some of the mafic phenocrysts have been altered to cholorite and calcite. The presence of rounded anorthosite xenoliths suggests possible contamination of the magma.

From the whole rock chemistry (Table 1) these rocks can be classified as alkaline lamprophyres, according to Rock (1987). Note the high concentration of alkalis, particularly K_2O. The SiO_2 contents of the dikes are similar to those of the camptonites of the Champlain Valley studied by McHone and Corneille (1980). Rock (1987) notes that lamprophyres have distinctly higher concentrations of Ba and Sr relative to other silicate igneous rocks, and this is shown here. The lamprophyres have Sr values ranging from 879 to 2016 ppm and Ba values of 800 to 1631 ppm (Table 1), as compared to the diabase dikes at Stop 2 (Rand Hill) which have Sr values of 334 to 706 ppm and Ba values of 373 to 496 ppm (Table 1).

These dikes are probably related to other lamprophyres of Mesozoic age found within the Champlain Valley which have been associated with the alkalic syenite gabbro intrusions of the Monteregian Hills of Quebec (e.g. McHone and Corneille, 1980; deBoer and others, 1988).
Continue west on Rt. 374.

3.2 5.6 Turn right (north) onto Rt. 190 (Old Military Turnpike)

6.4 12.0 **STOP 2A.** RAND HILL DIKE SWARM

Road cuts along Rt. 190 immediately south of Murtaugh Hill Road. Examination will be made first of the roadcuts here which provide fresh 3D exposures of the

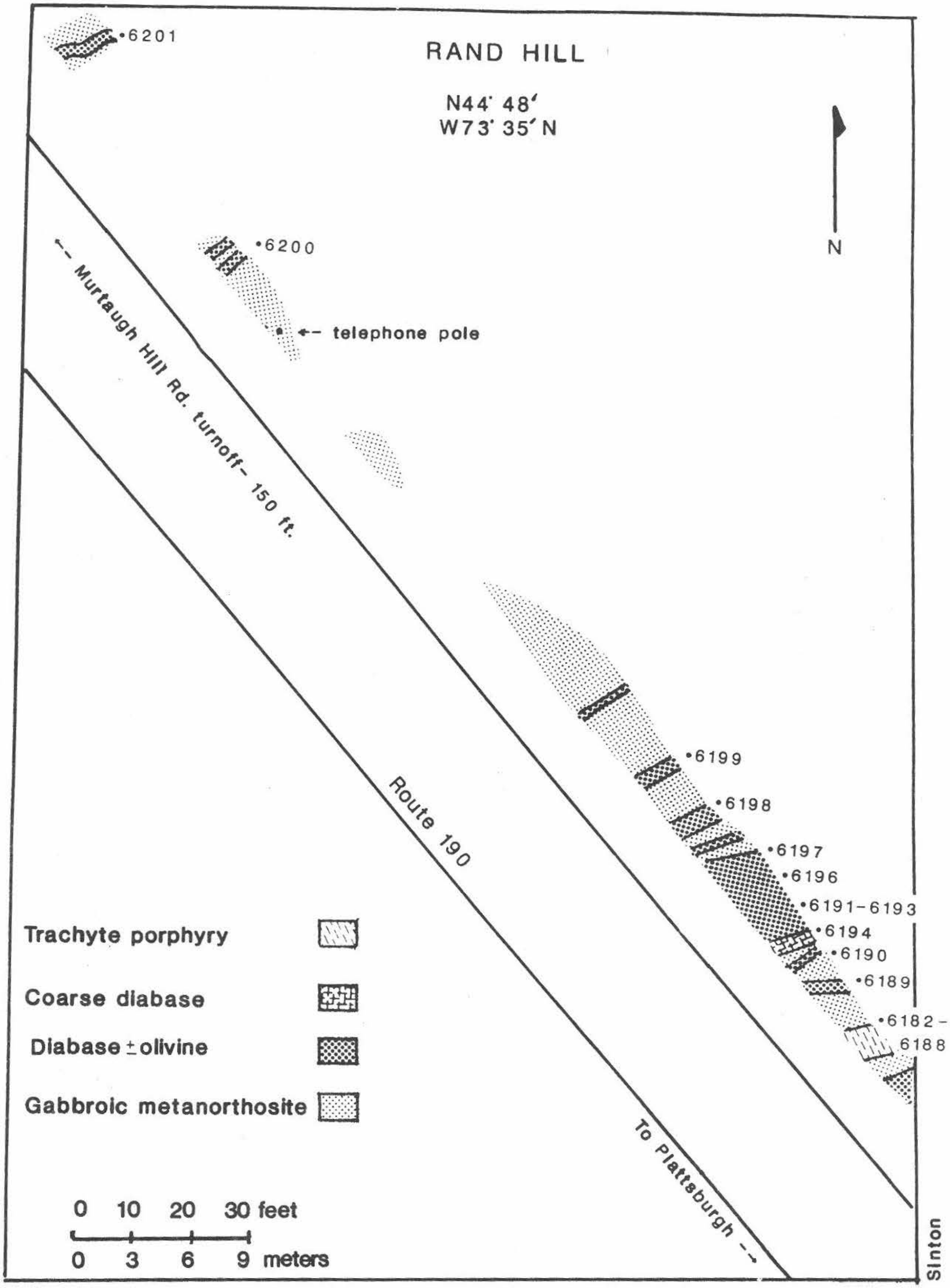


Figure 10. Pace and compass map of dike exposures on Rt. 190 at eastern flank of Rand Hill. Only dikes wider than 40 cm are shown. Sample site numbers are keyed to the chemical analyses of Table 1.

several dike types that make up the Rand Hill dike swarm. Very extensive exposures will then be examined in the largely open area that extends half a kilometer to the west, STOP 2B. The intruded country rock is gabbroic anorthosite gneiss.

The Rand Hill swarm is located at the eastern foot of Rand Hill. It was first described by H.P. Cushing (1898) who called attention to three localities in the northeastern Adirondacks with "exceedingly numerous dikes": Rand Hill, Dannemora Mountain, and the shores of Upper Chateaugay Lake. The Rand Hill dikes are nearly all vertical or sub-vertical, and consist of three types: diabase, olivine diabase, and trachyte porphyry (the "red syenite porphyry" of Cushing). Cushing noted that the thinner diabasic dikes are almost without exception porphyritic, and that the same applies to the borders of the wider dikes. In thin section, he found two generations of plagioclase and augite but only one of olivine. Biotite was observed in about 25 percent of the dikes.

Nineteen dikes are intruded into gabbroic meta-anorthosite in these road cuts. Their thicknesses range from 1 cm to 7 m. Some contain xenoliths and blocky plagioclase xenocrysts derived from incorporated host rock. The dikes are chilled at both their margins and along their contacts with xenoliths.

The distribution, dimensions, orientations, and classification of all dikes thicker than 40 cm is shown in Fig. 10. Dike identifications are based on field examination, including staining for K-feldspar, and then corroborated by thin section study. Numerous geochemical analyses were made in order to evaluate possible plate tectonic settings of the intrusions, as was discussed under Geochemistry.

The dominant dike type at Rand Hill is olivine diabase. Typically, altered olivine phenocrysts are concentrated in the central part of the dike by flow differentiation. The phenocrysts are altered to blackish serpentine clots (check hardness). The selective weathering of these clots accounts for the characteristic pitted surface. Although the olivines, with a specific gravity of 3.3 are concentrated in the centers of the dike by flow differentiation, the less dense plagioclase phenocrysts with a specific gravity of 2.7 are not; in fact they are generally concentrated in the finer grained border zones.

A 2.4 m wide trachyte porphyry dike with flow-aligned laths of Carlsbad-twinned plagioclase and K-feldspar is exposed near the southern end of the roadcut (sample numbers 6182-6188). It is typical of this group, although the color of these dikes vary: they may be either red, greenish, or gray to black. Cushing (1901) identified 19 trachyte porphyry dikes at Rand Hill and summarized their petrography. The essential minerals are microperthite and biotite, and accessory minerals are magnetite or specular hematite, hornblende, quartz, albite, orthoclase, microcline, apatite, and sphene; secondary minerals are chlorite, calcite, sericite, epidote,and hematite. Microperthite and biotite or chlorite are the only two minerals found in all dikes examined. Staining here shows that both K-feldspar and plagioclase laths are up to 1 cm long but vary in size and abundance. Total feldspar makes up about 55 percent of the rock, cholorite-altered biotite about 40 percent, and opaque minerals plus apatite needles the remainder. Note small blocky xenocrysts(?) of gray plagioclase and incorporated angular fragments of mafic dike rock. As discussed under Geochronology and Geochemistry, the diabase and trachyte dikes at Rand Hill are coeval, and presumably derived from a common magma source.

The northern contact of this dike is faulted, as indicated by shearing of the dike (probably cataclasis) and the introduction of anastamosing, hematite-stained calcite veins.

A small xenolith(?) of coarse-grained diabase or fine-grained gabbro (sample site 6194) adjoins the 7 m-wide olivine diabase dike at its southern margin (Fig. 10). The xenolith(?) is crosscut by a thin diabase dike that is chilled against it.

Relict ophitic texture is visible in the xenolith(?) although the rock is pervasively stained by oxides. It contains about 50 percent subhedral plagioclase and 20 percent relict orthopyroxene, most of it altered to serpentine and chlorite. Its similar composition (Table 1) suggests that it may be a cognate inclusion (autolith) brought up from a deeper level in the same magma system.

0.1 12.1 **STOP 2B.** RAND HILL DIKE SWARM

Turn left (west onto Murtaugh Hill Rd. and park. Walk across the road onto open hillocks that expose at least 100 mafic dikes in gabbroic anorthosite gneiss (Fig. 11). This locality, at the eastern foot of Rand Hill, is by far the best exposed mafic dike swarm in the Adirondacks. Dikes are intermittently exposed for lengths in excess of 150 m. Their thicknesses range up to at least 5 m. Ramble westward, in a zig-zag course across the dike swarm to the end of the

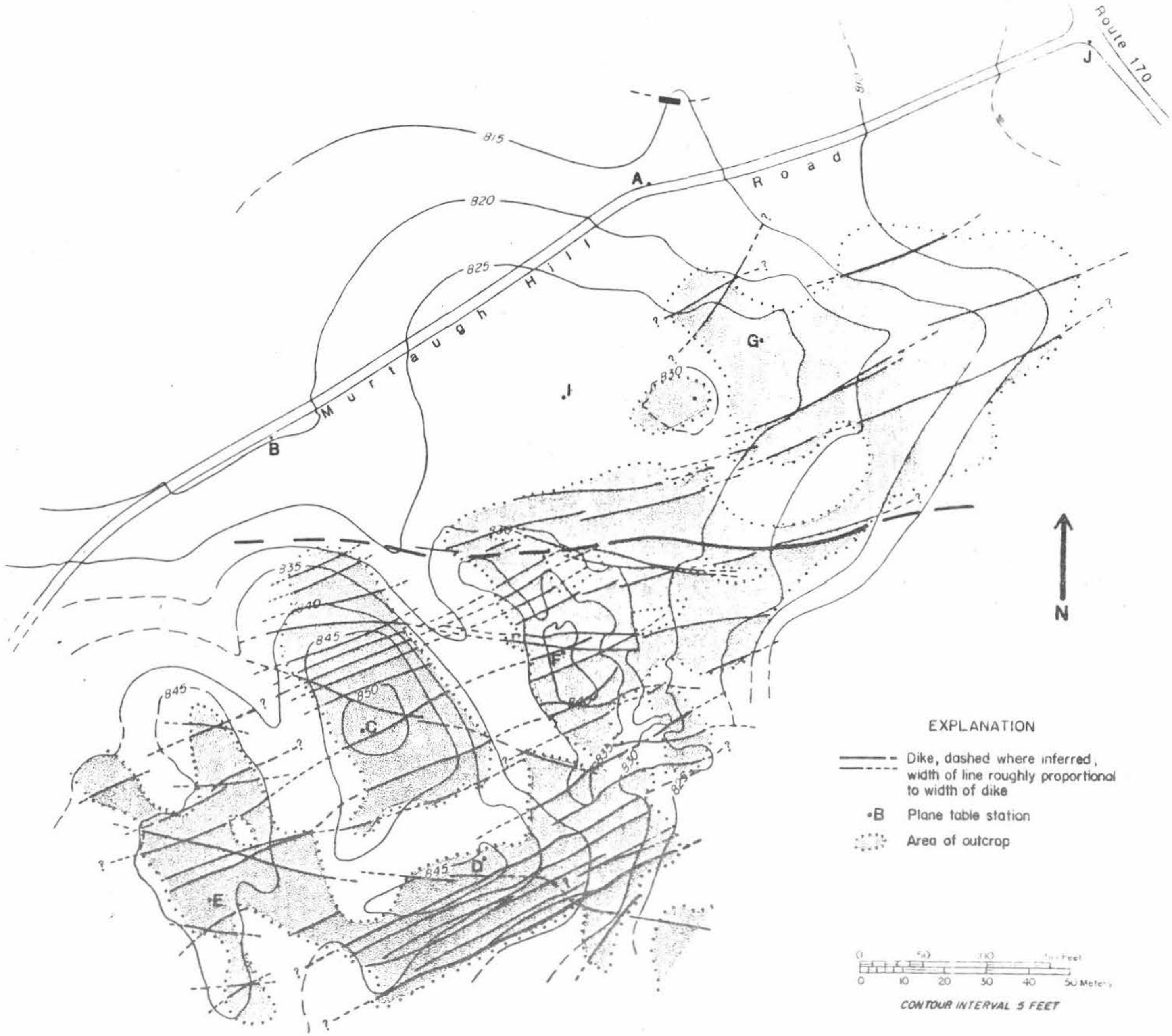


Figure 11. Plane table map of dike swarm on eastern flank of Rand Hill adjacent to Rt. 190. A few of the dikes shown are composites of two sheeted dikes, and some others are too closely spaced to be shown as separate dikes. More than 100 dikes are present here, representing three types: diabase, pitted olivine diabase, and trachyte porphyry. Modified after R. Barry, unpublished map. For location see Fig. 1.

exposure area about 350 m to the west. Exposures extend beyond the map area to the south and west.

Dikes here have three trends (Fig. 11), all cross-cutting the N30E strike of foliation in the host rock. The large irregular EW dikes bear alkali feldspar as shown by Kf staining. They are the "syenite porphyry dikes" of Cushing (1898). The N60-70E dikes are prophyritic olivine diabase dikes that show clear evidence of flow differentiation. Olivine phenocrysts that formed at depth have been concentrated in the centers of the rising magma by flow. The olivines are generally highly to completely altered, and weather out to produce the characteristic pitted surface. A N40E set is sparsely represented.

Note these interesting features of dikes during your ramble, and recall that basaltic dikes are emplaced almost instantaneously, the average velocity of propogation being 0.4-0.5 m/sec (Delaney and Pollard, 1982):

1) Chill borders against host rock.
2) Dikes may be straight, stepped, segmented.
3) Joints within the dikes do not penetrate the host rock: cooling cracks? compression features?
4) Dike walls may be even, irregular, cusped, and may have horn-like extensions or irregular apophyses.
5) Dike terminations may be tapered, blunt, rounded or irregular, and may have narrow extensions or "squirts".
6) Some dikes are composites of two sheeted dikes. The boundary between such dike pairs is a thin line of preferential erosion between the two adjacent chill borders. In at least one locality southwest of the mapped area, a sheeted dike pair bifurcates along strike around a slabbed inclusion of wall rock.
7) Relative age and direction of opening can be determined by analysis of dike intersections. These and en echelon configurations can also permit reconstruction of stress axes during emplacement. En echelon dikes indicate a reorientation of principal stress trajectories at the fingered propogation front of intrusive sheets (e.g. Delaney and Pollard, 1981).
8) Dike-parallel joints generally are absent in the host rock. This suggests that emplacement was not along pre-existing fractures but along an opening created and propagated by magma pressure in advance of the dike tip, in a plane perpendicular to the least compressive stress axis.
9) Concentration of olivine phenocrysts toward the center by flow differentiation.
10) Concentration of plagioclase phenocrysts near the margins rather than in the center.

11) Flow-aligned plagioclase laths indicate direction of magma propogation.
12) The amount of extensional strain produced by intrusion was significant in this swarm, reaching a magnitude of 18.8 percent north of Station C. A number of the dikes measured in this section could not be shown on the map of Fig. 11 because of its small scale.

Return southward on Rt. 190 to Rt. 374.

6.5	18.6	Turn left (east) on Rt. 374.
3.4	22.0	Intersection with NY Rt. 22 and Quarry Road; continue through intersection towards I-87.
0.5	22.5	Enter northbound entrance of (I-87), second right.
1.8	24.3	Turn right on NY 314 and continue straight through traffic light at NY Rt. 9 intersection.
1.45	25.75	Turn left at intersection between store on left and firehouse on right.
0.85	26.6	Turn left into private road.

STOP 3. CAMPTONITE DIKE

NO HAMMERS; cameras instead. Xenolith-filled augite camptonite dike, Martin Bay. Private property; permission required of landowner.

The dike makes a low garden wall that strikes N80W. It is 0.5 m thick, and exposed over a length of 7m.

The place to concentrate on, however, is along the shore, where an isolated block of dike rock, 70 cm thick, has weathered out of its host rock, the Cumberland Head Argillite (Middle Ordovician). Note the parallel dike walls bordering the 10 cm-thick fine-grained chill margins. Note also the striking number of xenoliths concentrated in the 50 cm-thick central part of the dike by flow differentiation. These subangular to round xenoliths constitute about 50 percent of the dike, and appear megascopically to have sharp boundaries with the dike material. They range in diameter from 1 mm to 9 cm, most exceeding 2 cm. Lithologies include pyroxene syenite gneiss, gabbroic metanorthosite, metagabbro, and trachyte, as well as one ultramafic xenolith and a round xenocryst of hornblende. Note the slight flow alignment of elongate xenoliths.

In crushed grains and thin sections D.H. Newland (in

Hudson and Cushing, 1931) found that the syenitic inclusions contain microcline, microperthite, much-altered greenish pyroxene, and iron-stained grains that may be hornblende, biotite or both, along with small amounts of quartz, and occasional garnet crystals. The dike material is a fine-grained holocrystalline lamprophyre with phenocrysts of clinopyroxene and olivine in a felted groundmass of plagioclase, augite and opaque oxides. Staining indicates about 20% K-feldspar in the groundmass.

The xenoliths are typical of Adirondack rock types, so their source along the path of intrusion is easy to visualize. What is unusual is the fact that 1) among the 250 lamprophyre and trachyte dikes in the Lake Champlain area of New York and Vermont (McHone and Corneille, 1980) such xenoliths are extremely rare, and 2) the xenoliths are so remarkably rounded. Does the abundance in this one dike suggest that the magma advanced through a brecciated and fragmented fault zone? through a basal Paleozoic conglomerate? If the latter, the xenoliths are considerably larger than the pebbles in the rare exposures of basal Potsdam in the eastern Adirondack region. If the former, was the rounding produced by mechanical abrasion of incorporated breccia? by melt abrasion or partial resorption?

This particular dike gives a K/Ar date of 131±5 Ma (Greg McHone, written comm., 2-19-85) which falls in the age range of the NY-Vt. lamprophyres and corresponds to the oldest ages of the Monteregian Hills intrusions of Quebec (McHone and Corneille, 1980).

A similar xenolith-laden dike is well exposed farther south, in Indian Bay, Willsboro Point. It is an augite camptonite dike, more than 2 m thick, intruding Canajoharie Shale (Middle Ordovician). It is pictured and described by Buddington and Whitcomb (1941). McHone (written comm., 2-19-85) reports a K/Ar age of 119±5 for this dike.

The narrow range of strike of the lamprophyre <u>and</u> trachyte dikes, in the Lake Champlain valley, as well as the consistency of Cretaceous ages, suggest that they are a cogenetic suite, perhaps a mafic-felsic pair formed by an immiscible liquid mechanism from mantle-derived camptonitic magma (McHone and Corneille, 1980).

Return to Rt. 9. Turn left to Plattsburgh, or straight ahead to enter the Northway (I-87).

REFERENCES CITED

Bourne, J. and Hogarth, D.D., 1978, The Grenville Supergroup and younger rocks of the Gatineau-Lieore region: Ottawa, Ontario, Grenville Club Annual Meeting Fieldtrip Pamphlet.

Brown, L.L., 1982, Anomalous paleomagnetic directions from Paleozoic(?) dikes, northeast Adirondacks: Geol. Soc. America, Abstracts with Programs, v. 14, p.8.

Buchan, K.L., Farig, W.F., Freda, G.N., and Frith, R.A., 1983, Paleomagnetism of the Lac St-Jean anorthosite and related rocks, Grenville Province, Quebec: Can. J. Earth Sci., v. 20, pp. 246-258.

Buddington, A.F., and Whitcomb, L., 1941, Geology of the Willsboro quadrangle, New York: New York State Museum Bulletin 325, 137p.

Coish, R.A., Fleming, F.S., Larsen, M., Poyner, R., and Seibert, J., 1985, Early rift history of the proto-Atlantic ocean: geochemical evidence from metavolcanic rocks in Vermont: Am. J. Sci., v. 285, p. 351-378.

__________ and Sinton, C.W., 1988, Opening of Iapetus: Rift & Ridge volcanics in Vermont. Ann. Meeting Geological Association of Canada, abstr. with programs, v. 13, p. A23.

Cushing, H.P., 1898, Syenite porphyry dikes in the northern Adirondacks: Geol. Soc. America Bull., v. 9, p. 239-256.

__________, 1901, Geology of Rand Hill and vicinity, Clinton County: New York State Mus., 53rd Ann. Rept. of the Regents for the year 1899, p. r37-r82.

Dalrymple, G.B. and Lamphere, M.A., 1969, Potassium-argon dating, principles, techniques and applications to geochronology: W.H. Freeman and Company, San Francisco, 258p.

deBoer, J.Z., McHone, J.G., Puffer, J.H., Ragland, P.C., and Whittington, D., 1988, Mesozoic and Cenozoic magmatism: in The geology of North America, v. 12, The atlantic continental margin: U.S. The Geol. Soc. Amer., p. 217-241.

Delaney, P.T., 1982, Solidification of basaltic magma during flow in a dike: Amer. Jour. Sci., v. 282, p. 856-885.

__________, and Pollard, D.D., 1981, Deformation of host rocks and flow of magma during growth of minette dikes and breccia-bearing intrusions near Ship Rock, New Mexico: U.S. Geol. Survey Prof. Paper 1202, 61p.

Friedman, G.M., 1987, Deep-burial diagenesis: its inplications for vertical movements of the crust, uplift of the lithosphere, and isostatic unroofing - a review: Sedimentary Geology, v. 50, p. 67-94.

Geraghty, E.P., Isachsen, Y.W., and Wright, S.F., 1979, Dikes of Rand Hill, northeast Adirondacks, as paleostrain indicators: U.S. Nuclear Regulatory Commission Report NUREG/CR-0889, 13p.

Goldberg, S.A., Butler, J.R., and Fullagar, P.D., 1986, The Bakersville dike swarm: geochronology and petrogenesis of late Proterozoic basaltic magmatism in the Southern Appalachian Blue Ridge: Am. Jour. Sci. v. 286, p. 403-430.

Haggerty, S.E., 1976, Oxidation of opaque mineral oxides in basalts: in Oxide Minerals, Min. Soc. of America Short Course notes, v. 3, pp. hg-1 - hg-98.

Hatch, F.H., Wells, A.K., and Wells, M.K., 1973, Petrology of the igneous rocks: Hafner Press, 551p.

Heizler, M.T. and Harrison, T.M., 1987, The ups and downs of the Northeastern U.S. from the Proterozoic to the Jurassic: Geol. Soc. America Abstracts with Programs, v. 19, No. 7, p. 698.

Hudson, G.H. and Cushing, H.P., 1931, The dike invasions of the Champlain Valley, New York: New York State Mus. Bull. 286, p. 81-112.

Irving, E., and McGlynn, J.C., 1976, Proterozoic magnetostratigraphy and tectonic evolution of Laurentia: Phil. Trans. Roy. Soc. of London, Series A, p. 433-468.

Isachsen, Y.W., and McKendree, W.G., 1977, Preliminary brittle structures map of New York: New York State Museum Map and Chart Series No. 31.

______________, and Seidemann, D., 1983, Dike orientations in basement rocks of the Adirondack dome, New York, and regional paleostrain history as deduced using their K/Ar ages: 5th Irternational Conference on Basement Tectonics, Cairo, 1983, Abstracts of Papers, p. 30.

______________, Geraghty, E.P., and Wiener, R.W., 1984, Fracture domains associated with a Neotectonic, basement-cored dome- The Adirondack Mountains, New York: in Gabrielsen and others, eds., Proceedings of the Fourth International Conference on Basement Tectonics, Basement Tectonics Association, p. 287-305.

______________, and Wright, S.F., in press, Dike Map of the Adirondack Mountains, New York: New York State Museum Map and Chart Series.

Johnsson, M.J., 1986, Distribution of maximum burial temperatures across northern Appalachian Basin and implications for Carboniferous sedimentation patterns: Geology, v. 14, p. 384-387.

Kemp, J.F., and Marsters, V.M., 1893, Trap dikes of the Lake Champlain region: U.S. Geol. Survey Bull. 261, 126 p.

McDougall, I., and Harrison, T.M., 1988, Geochronology and Thermochronology by the $^{40}Ar/^{39}Ar$ Method: Oxford Univ. Press, New York (in press).

McHone, J.G., 1984, Mesozoic igneous rocks of northern New England and adjacent Quebec: Geol. Soc. Amer. Map and Chart Series MCH-049.

__________, and Corneille, E.S., 1980, Alkalic dikes of the Champlain Valley: Vermont Geology, v. 1, p. 16-21.

Pearce, J.A., and Cann, J.R., 1973, Tectonic setting of basic volcanic rocks determined by using trace element analysis: Earth and Planet. Sci. Lett., v. 19, p. 290-300.

__________, Gorman, B., and Birkett, T., 1977, The relationship between major element chemistry and tectonic environment of deposition of basic and intermediate rocks: Earth Planet. Sci. Lett., v. 36, p. 121-132.

Pollard, D.D., 1987, Elementary fracture mechanics applied to the structural interpretation of dykes: in Halls, H.C. and Fahrig, W.F., eds Mafic dyke swarms: Geol. Assn. Canada Sp. Paper 34, p. 5-24.

Rankin, D.W., 1976, Appalachian salients and recesses: Late Precambrian continental breakup and the opening of the Iapetus Ocean: Jour. Geophys. Research, v. 81, p. 5605-5619.

Ratcliffe, N.M., 1987, High TiO_2 metadiabase dikes of the Hudson Highlands, New York and New Jersey: possible late Proterozoic rift rocks in the New York recess: Am. Jour. Sci., v. 287, p. 817-850.

Rickard, L.V., 1988, Stratigraphy of the subsurface Lower and Middle Devonian of New York, Pennsylvania, Ohio and Ontario: New York State Mus. Map and Chart Series No. 39.

Rock, N.M.S., 1977, The nature and origin of lamprophyres: some definitions, distinctions, and derivations: Earth Science Reviews, v. 13, p. 123-169.

Roy, J.L., and Robertson, W.A., 1978, Paleomagnetism of the Jacobsville Formation and the apparent polar path for the interval -1100 to -670 m.y. for North America: J. Geophys. Res., v. 83, pp. 1289-1304.