MESOZOIC DIKES AND TECTONIC FEATURES IN THE CENTRAL CONNECTICUT RIVER VALLEY, VERMONT AND NEW HAMPSHIRE

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INTRODUCTION

Jurassic and Cretaceous igneous-tectonic events in northern New England produced a large number of diabase and lamprophyre dikes, which overlap in distribution but also range widely away from the plutonic complexes of the Early Jurassic White Mountain Magma Series and Early Cretaceous New England-Quebec Igneous Province. In consequence, boundaries of the igneous provinces are better defined by the dike swarms than by the larger plutons. Many high-angle faults and fractures, and much regional uplift in New England also date to these times. Dikes are tectonic as well as igneous features, and a major brittle fault zone appears to have been active along the Connecticut River area, with some faults crosscutting the intrusions. In some places there are distinct boundaries for intrusional members of provinces, which may be related to active lithospheric structures (McHone, 1996a; McHone and Shake, 1992). However, it is not always easy to connect small local features to particular large regional events.

Previous field guides for NEIGC and local geological societies have described Mesozoic dikes in other regions of northern New England (Fig. 1), but this is the first to our knowledge for the central Connecticut Valley border of Vermont and New Hampshire. There are many more small mafic and a few felsic dikes in the region (see Ratcliffe and others, 2011) but most are hard to get to or occur along limited access highways where stops are not allowed. We will visit several relatively accessible locations, where we can examine and discuss mafic dikes that rose from their mantle sources in concert with faulting during the Mesozoic Era, a time of great activity in New England.

MESOZOIC IGNEOUS PROVINCES

The long history of work on post-metamorphic igneous rocks in New England has brought slow but continuing progress in our understanding of the sequence of magma generations and their relation to tectonic events. The list of references for this field guide includes a partial bibliography for our field region. The large plutonic complexes have had most of the attention from petrologists over the past centuries, so since the 1970s we have focused on the dike swarms that are spread across northern New England. Our philosophy is that the geological value of a feature is not proportional to its size! As in many areas of geology, the subject has few people working on it, so if you or students are interested, please jump in!

There are about 1100 dikes on the Mesozoic intrusion map by McHone (1984) but many more exist, and new ones are frequently exposed by construction projects. Field work for the new Vermont bedrock map (Ratcliffe and others, 2011) added a hundred or more dikes, and this excellent map is one of the few that show dikes on a state-wide scale (but you have to look close!). Many of the dikes must be co-magmatic and connected, that is, mafic magmas have probably split and branched from larger into smaller dikes as they rose from mantle sources. These were fluids of relatively low viscosity due to high volatile contents, so they moved quickly with mainly laminar flow McHone, 1978a). There is little to no evidence that the small dikes reached the surface, which was probably a few km above the present levels in Early Cretaceous times, but it is possible that some created small volcanoes. A big volcano must have existed over the current Ascutney Mountain plutonic complex, which contains large inclusions interpreted as volcanic products that settled into the upper magma chamber (Daly, 1903). The same is true for some large Mesozoic plutons in New Hampshire (Creasy and Eby, 1993).

Dike rocks of the different generations can often be categorized through careful examination of hand samples. Most of the dikes are fine-grained but holocrystalline as well as porphyritic, and many have obvious igneous structures such as flow bands. Thin sections are always very useful, and in some cases they are indispensable for characterizing the petrography and classification. It is important to improve our knowledge of the types and distribution of Mesozoic intrusions because there appear to be definite boundaries to these igneous provinces in New England (Fig. 1; McHone and Butler, 1984; McHone and Sundeen, 1995). The igneous province boundaries could be due to tectonic controls such as terrane boundaries and major faults, or specific mantle melt zones may be featured. We will discuss the physical and geographic distinctions of these rocks during this trip.

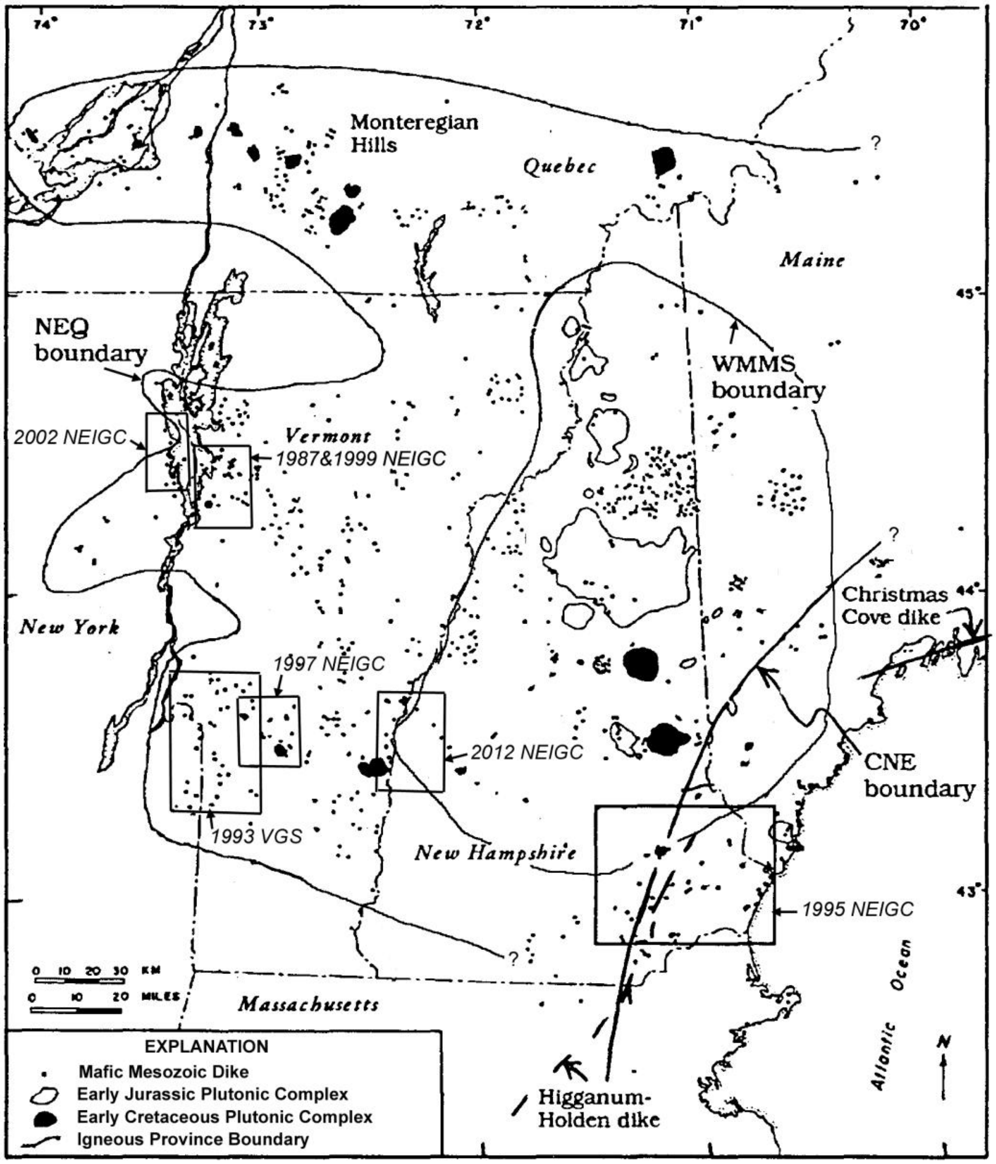


Figure 1. Mesozoic igneous provinces of northern New England, with dike-defined boundaries modified after McHone and Butler (1984). Areas covered by various field guides have rectangular outlines (VGS = Vermont Geological Society). The distribution of "dike dots" is a function of detail reported in quadrangle bedrock maps (resulting in clusters or gaps) as well as actual regional abundance. Province abbreviations: CNE = Coastal New England; WMMS = White Mountain Magma Series; NEQ = New England – Quebec.

Even before the determination of Mesozoic ages for plutons of the White Mountain magma series (principally by Foland and others, 1971 and Foland and Faul, 1977), many geologists lumped all post-metamorphic igneous rocks of northern New England as White Mountain Magma Series, commonly labeled WMMS. Because most of the WMMS dikes, stocks, and batholiths display alkalic igneous characteristics (Ti-rich clinopyroxene and alkali amphibole; abundant alkali feldspar; high K, Na and Th contents), it has seemed logical to relate them to differentiation or fractionation of intra-plate mantle or crustal melts that have some common genesis (Foland and others, 1988; Creasy and Eby, 1993). Although some examples show hydrothermal alteration and igneous fabrics, the Mesozoic igneous rocks lack metamorphic foliations and S-type granites that distinguish the common Paleozoic plutons in New Hampshire.

Additional work (McHone and Butler, 1984) reinforced the age divisions of Foland and Faul (1977) into groups with Middle Triassic (220-235 Ma), Early to Middle Jurassic (175-195 Ma) and Early Cretaceous (100-130 Ma) ages, with a few important exceptions (Belknap Mountain is probably close to 160 Ma). We use names and acronyms of Coastal New England (CNE), White Mountain Magma Series (WMMS), and New England-Quebec (NEQ) for the provinces, from older to younger. Additional and separate tholeiitic magmatism around the Triassic-Jurassic boundary (201 Ma) filled Early Mesozoic rift basins of eastern North America with thick flood basalts derived from volcanic fissures, which are now shown by very large feeder dikes (McHone, 1996b). The largest of these giant dikes is the Higganum-Holden-Christmas Cove dike (Fig. 1). The younger Bridgeport-Pelham Dike trends toward west-central New Hampshire and may be present near Claremont (Filip, 2010), but more confirmation is needed. Apparent boundaries for Mesozoic igneous provinces in northern New England are shown in Figure 1.

A major problem is that Early Jurassic WMMS intrusions include many alkalic diabase and lamprophyre dikes that are similar to members of the Cretaceous NEQ and the Triassic CNE provinces (described below). To date, however, all such look-alikes are found only in New Hampshire and western Maine (McHone and Trygstad, 1982; McHone, 1992; McHone and Sundeen, 1995), a geographic association that makes it easy to call them members of the White Mountain Magma Series. McHone and Butler (1984) proposed that the alkalic Early Jurassic plutons and dikes of the WMMS are a cohesive province only in central and northern New Hampshire (into northeastern-most Vermont), and western Maine (at least to the Rattlesnake Mountain pluton). We do not know of any *proven* Triassic or Early Jurassic dikes in Vermont, only Early Cretaceous intrusions of the New England-Quebec igneous province.

Although magmas of all the Mesozoic divisions overlap in New Hampshire, the Early Cretaceous intrusions range across a much wider province that includes the Monteregian Hills of southern Quebec, dense swarms of lamprophyre dikes in western Vermont and eastern New York, and scattered dikes through New Hampshire and southern Maine (McHone, 1984; McHone and Sundeen, 1995). Based on similar ages and petrological characteristics, the Early Cretaceous intrusions were regrouped as the New England-Quebec (NEQ) igneous province by McHone and Butler (1984).

PETROLOGIC CONSIDERATIONS

Local dike types include alkali diabase, monchiquite, camptonite, spessartite, and bostonite, the last two of which will not be examined during this trip. All of these igneous types are presumed to be related through some upper mantle to upper crustal paths of fractional melting, differentiation, contamination, and crystallization, but it is unlikely that they were at one time all co-magmatic. However, the alkali syenite and gabbro members of the Ascutney Mountain complex are derived from the same magmatic sources as the dikes (also see Eby, 1985a; Schneiderman, 1991).

Alkali Diabase is relatively plagioclase rich although the feldspars may be altered to clay or sericite. Augite and minor biotite in the groundmass often look oxidized, and some contain small but completely altered olivine crystals. Most alkali diabase dikes are fine-grained and non-porphyritic, but some show prominent plagioclase phenocrysts. The diabase is essentially altered dolerite in dikes of hypabyssal alkali basalt or sub-alkaline tholeiite. *Monchiquite* is a very mafic, granular, analcite-bearing, olivine or biotite-bearing, augite-rich alkali basalt similar to nephelinite, often also with calcite in separate grains or clumps (or replacing mafic minerals), phlogopitic mica, and kaersutitic hornblende. Feldspars are poorly developed or lacking. Monchiquite is commonly dark gray in color and relatively dense, but phenocrysts of mafic minerals are visible. *Camptonite* can look much like monchiquite, except that olivine is rare or absent, kaersutite is common to abundant, and plagioclase is more abundant than analcite. Phenocrysts are also mafic (augite and/or kaersutite), only very rarely felsic. Camptonite dikes usually have a brownish to gray range of colors, lighter than monchiquite. Camptonite is the hypabyssal equivalent of basanite.

Spessartite dikes lack olivine and analcite, but plagioclase (intermediate Ca) is well developed and present as phenocrysts as well as intergrown with augite in the groundmass. Phenocrysts or megacrysts of kaersutite serve to distinguish spessartite from alkali diabase dikes common in eastern New England. Spessartite often shows a distinctly greenish or purplish cast as well as gray colors. *Bostonite* is a name that in a strict sense applies only to felsic (anorthoclase-rich) dikes that have a "felty" clumped-grain feldspar texture, which is not always present. Trachyte, although used for volcanic rocks as well, is a better general term. Minor minerals include oxidized biotite, quartz, and clay products. Some examples show well-formed alkali feldspar and/or quartz phenocrysts. Trachyte dikes may be iron-stained, but they are generally light brown to cream-colored on fresh surfaces. Felsite dikes associated with the Ascutney Mountain plutonic complex (Balk and Krieger, 1936) may be bostonite.

Although small, lamprophyre dikes of the New England-Quebec province are numerous and widespread, with a consistent range of compositions across the 400+ km width of the province (McHone, 1978a). The dikes both predate and postdate the larger plutonic complexes (although perhaps not by much), while their distribution suggests that the alkalic lamprophyres are not offshoots from those plutons. Major and trace element compositions, and isotopic ratios of the lamprophyres are similar to world-wide alkali-olivine basalts, basanites and nephelinites (McHone, 1978a; Eby, 1985a), although lamprophyres have higher concentrations of H_2O+ (1-3 %) and CO_2 (commonly 2-4 %). As per the definitions of Rock (1977), alkali lamprophyres generally have phenocrysts of mafic minerals but few or none of feldspar.

There are only a few whole-rock analyses available for dikes in the area (Table 1). Alkali diabase dikes of the WMMS commonly show SiO_2 values between 46 and 50 weight percent, TiO_2 above 2 weight percent, and K_2O near 1 weight percent (but it varies). NEQ lamprophyres have similar high Ti and alkalies but lower SiO_2, usually 39 to 45 weight percent. The low-silica examples are usually monchiquite, which has more analcime or feldspathoid than feldspar in the matrix. Camptonite usually has more Si but less Mg than monchiquite, unlike these analyses.

TABLE 1. CHEMICAL ANALYSES OF LOCAL DIKES

Sample	CL-3	HN-4	HN-10	Daly
SiO_2	42.04	47.62	42.00	49.63
TiO_2	2.52	2.62	2.59	1.68
Al_2O_3	14.07	14.73	12.10	14.40
Fe_2O_3t	12.16	12.88	10.52	10.91
MnO	0.20	0.16	0.14	0.17
MgO	9.26	4.83	11.23	7.25
CaO	10.89	10.23	15.48	9.28
Na_2O	2.63	2.72	2.81	2.47
K_2O	1.48	0.78	1.26	0.70
P_2O_5	1.03	0.30		0.25
H_2O+	2.97	1.49		1.47
CO_2	0.20	1.31		1.36
H_2O-	0.51	0.83		0.27
Total	99.97	100.41	98.24	99.84

Samples:
CL-3 = Exit 8 monchiquite north of CL-4 (McHone, 1978b)
HN-4 = alkali diabase I-89xI-91 (McHone, 1978b)
HN-10 = camptonite Hartland Dike, unpub. microprobe data
Daly = diabase dike near Ascutney Mtn. (Daly, 1903)

The alkali diabase often show low temperature hydrothermal alteration (clay, iron oxidation) while lamprophyre minerals have higher-temperature replacement products (biotite, zeolite, serpentine). Volatiles contents are high, but modern analytical techniques often list only anhydrous compositions. "Loss on ignition" (mostly H_2O and CO_2) values typically range from 3 to 5 weight percent (McHone, 1978b) for alkali diabase and lamprophyres. Water and carbon dioxide in magma retard the crystallization of feldspar, and if primary will encourage biotite and basaltic amphibole (kaersutite) to form, as well as calcite. Olivine when present usually looks unstable, with rims or complete replacement by calcite and serpentine. Water introduced from the host rocks after crystallization at depths of 4 to 6 km are possible for the Jurassic alkali diabase dikes, while water and carbon dioxide as original components of basanitic magma are more likely in the Cretaceous lamprophyre dikes, which may have crystallized at depths closer to 2 km.

Work by Hodgson (1968), McHone (1978), Eby (1985a) and others shows that the regional lamprophyric magmas cannot be derived from a common parent through differentiation or assimilation, but must instead reflect different initial compositions followed by crystal and chemical fractionation. Eby (1985a) has argued that isotopic characteristics of the dike rocks show their origin to be partial melts of a heterogeneous spinel lherzolite mantle.

Mantle xenoliths in the North Hartland dike and other localities in New England and Quebec are spinel-bearing types that represent mantle rocks above the source melts, with a few high-pressure cumulates from ponded magmas

(Raeside and Helmstaedt, 1982). Thus, the xenoliths indicate a direct mantle origin for lamprophyres in common with other alkalic basalts. Melting of the mantle to form such magmas may depend upon metasomatic events that add K, Ti, water, and other components (Windom and Boettcher, 1980; Eby, 1985a).

REGIONAL TECTONIC FEATURES

The major bedrock differences between the eastern Vermont lithologies (Connecticut Valley Synclinorium or Trough) and western New Hampshire formations of the Bronson Hill Anticlinorium with its structures have challenged many field geologists. The boundary between Devonian (?) Waits River and Gile Mountain carbonates and phyllites of the "Vermont sequence" and Ammonoosuc meta-volcanics of the "New Hampshire sequence" passes through the field area, and near to dikes at stops 1, 2, and 4. This boundary was mapped as an unconformity known as the Monroe Line, but Hatch (1988) presented evidence for at least two periods of faulting (Acadian thrusting (?) and Mesozoic normal faulting) along the boundary, and the original name Monroe Fault was reinstated.

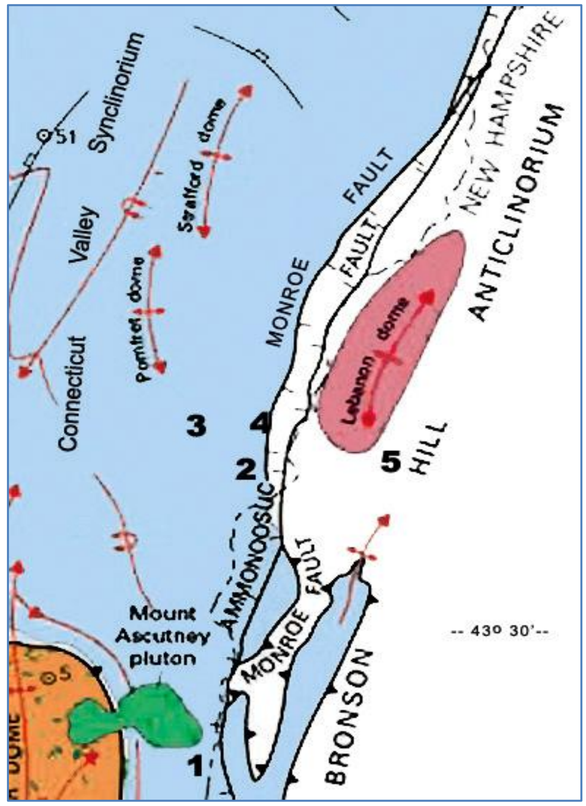


Figure 2 (right). Major structures in the field guide area, adapted from an inset of the Vermont bedrock map (Ratcliffe and others, 2011). Dike locations are numbered as the stops in this guide.

Although it might be reactivated from a much older terrane boundary structure, the Ammonoosuc fault extends southward along the Connecticut River, and connects by a transfer fault south of Fall Mountain, NH, with the eastern border fault of the Early Mesozoic Deerfield Basin, where at least 4 km of strata are offset by Jurassic or younger faulting (Zen and others, 1983). In a pioneering study for dating faults, Lyons and Snellenburg (1971) reported K-Ar ages near 160 Ma for sericite generated in brittle faults around Sunapee and Grantham, New Hampshire. These high-angle faults extend southwesterly to connect with the Ammonoosuc Fault and Mesozoic border fault (Lyons and others, 1997).

Mesozoic uplift and fault tectonism in New England have been shown to extend into Cretaceous and possibly later times by apatite and zircon fission track studies (Doherty and Lyons, 1980; Roden-Tice and others, 2012). Regional bedrock formations, metamorphism, and orogenic events may be old, but the mountains, valleys, and other landforms we see today are relatively young. As Yngvar Isachsen explained to us (pers. comm. 1973; Isachsen, 1981), erosion rates are too fast for high-relief mountains to be very old, and relatively high elevations of the Appalachians and Adirondacks are due to Late Mesozoic and Tertiary uplift (Roden-Tice and others, 2009).

Thus some major high-angle faults in the region have significant offset dating from Middle Jurassic times, with activity continuing to affect NEQ dikes as well. Several mafic dikes in this zone are cut by high-angle faults with offsets of a few meters or less, although these may only be sympathetic movements along particularly weak foliation planes, which tend to be steeply dipping and sub-parallel to the major faults. The Early Cretaceous NEQ intrusions are aligned with NW-SE dike trends in Quebec and possibly northwestern Vermont (McHone and Shake, 1992), but large WMMS plutons trend more N-S in New Hampshire (Fig. 1). Dike trends across eastern Vermont through New Hampshire and western Maine vary, but most commonly they are NE-SW (McHone, 1984). We see little evidence that dikes intrude faults, but they do follow local joints and/or cleavage foliations in many outcrops.

TABLE 2. DIKES IN EASTERN VERMONT KNOWN OR SUSPECTED TO BE FAULTED

I.D.	Location & Comments	Dike Strike & Dip	Width in cm	Dike Type	Fault Strike & Dip	Offset in cm	Type
BA-3	44°05;40"N 72°36'42"W	N85E, 76N	41	aug.camptonite	N9E, 40W	36	(reverse)
	On I-89. Fault and gouge well developed						
BA-8	44°05'41"N 72°36'42"W	N70E, 87N	20	aug.camptonite	N11E, 24E	14	(normal)
	On I-89. Clean fracture, follows country rock cleavage.						
RD-3	43°57'12"N 72°37'41"W	N56E, 75S	63	hbl.camptonite	N2W, 74W	17	(normal)
	South of the Bethel exit of I-89. Fault and gouge well defined.						
RD-4	43 57'10"N 72°37'41"W	N60E, 63S	6-47	hbl.camptonite	not measured	?	(normal)
	Near RD-3. Fault looks similar to RD-3						
HN-5	43°38'15"N 72°20'32"W	N5W, 82S	43	alkali diabase	N12W, 38W	35	(normal)
	Shows internal slickensides						
HN-9	43°40'09"N 72°18'51"W	N84E, 89S	43	alkali diabase	N24E, 34NW	15	(normal)
	Clean fracture, little gouge						
HN-10	43°40'09"N 72°18'51"W	N66E, 68SE	7	alkali diabase	N32E, 55NW	60	(normal)
	Clean fracture, little gouge						
HN-15	43°36’19”N 72°21’29”W	N74E, 68SE	33-49	aug. camptonite	N10E, 80W	50-90	(normal)
	Two offsets of the dike show in western spillway cut, which appear to follow the cleavage						

Abbreviations: hbl. = hornblende; aug. = augite
The i.d. code is based on 15' quad names: BU=Burlington; BA=Barre; RD=Randolph; WR; HN=Hanover.
HN-5, 9, and 10 are in the intersection of I-89 with I-91 in White River Junction. HN-15 Is the North Hartland Dike.

Ascutney Mountain Complex

Daly (1903), Chapman and Chapman (1940), and a few later workers suggested that mafic lamprophyre and diabase dikes, with some felsic dikes, radiate around Ascutney Mountain, an Early Cretaceous (122 ±1 Ma; Hubacher and Foland, 1991) bimodal complex of gabbro-diorite, alkali syenite, and alkali granite (Schneiderman, 1991). Only a few dikes appear to cut the complex, but lamprophyres are relatively abundant in the local area, including monchiquite as well as camptonite and alkali diabase types. The suggestion is that the dikes preceded the sub-volcanic magma chambers, which subsequently cooled into the present complex.

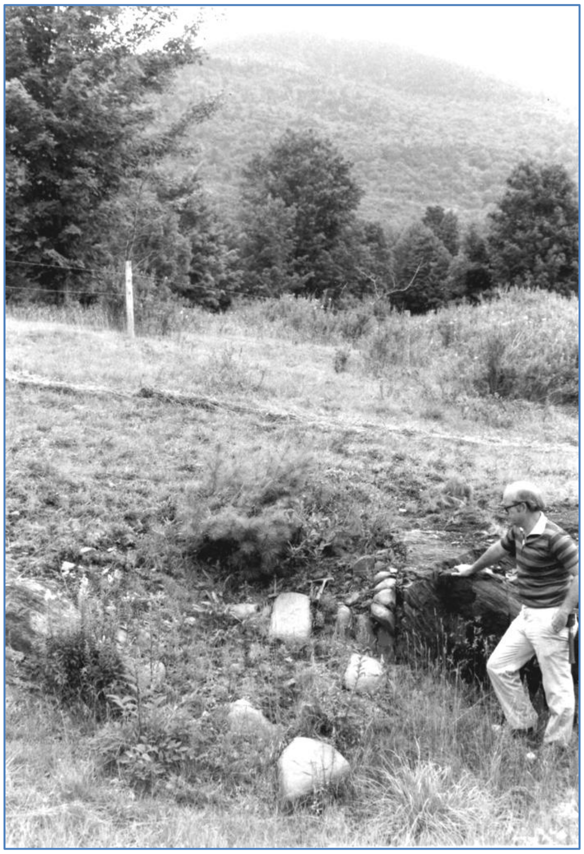


Figure 3 (left). A lamprophyre dike in a field north of Rte. 131 trends toward the southern side of Ascutney Mountain. A chain of rounded cobbles comprise the eastern side of the small dike, as Bob Butler is observing in 1977. Rounding by "onion skin" chemical weathering is found mainly in natural surface exposures rather than cuts.

Maps by McHone (1984) and Ratcliffe and others (2011) appear to show more variation in dike trends near Ascutney rather than the more common northeasterly trends of eastern Vermont and New Hampshire. Some of the local dikes are not radial, however, and the trend variations may be more due to local stress disruption than flow from the crustal volcanic center.

We prefer a model in which the dikes represent the same mantle melts that were collecting into large bodies or chambers in the deep lithosphere. The dikes therefore are more primary than the Ascutney plutonic types, which formed by crystal-liquid or liquid-liquid fractionation during their slow rise into the upper crust.

Sunapee Dike and Uranium Occurrence

Although you may pass it on the way this is not a stop, and anyway the NH highway department removed the critical highway cut some years ago, but we take this opportunity to mention a somewhat notorious lamprophyre dike and associated uranium mineralization near Sunapee.

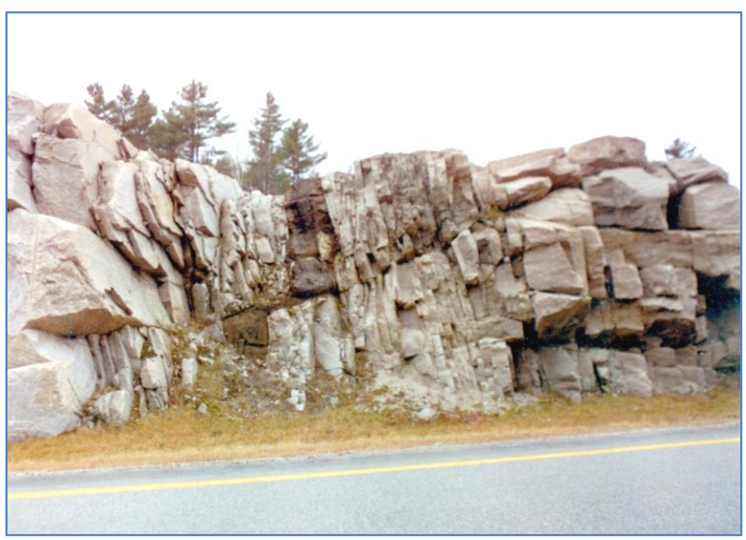


Figure 4 (right). The Sunapee Dike in a former road cut of the center median in I-89, N-bound lane looking west.

The dike was visited by Greg McHone during studies of lamprophyre dikes in New England in the 1970s (McHone, 1978b) and later for work on the uranium mineralization in the region (McHone and Wagener, 1980a and b), which was part of the federallyfunded National Uranium Resource Evaluation (NURE) program. Wally Bothner (1978) had already produced a very useful study of this and other U occurrences in New Hampshire.

The mafic dike and road cut between the north and south-bound lanes of I-89 were a bit less than 1 km south of exit 12. Our dike i.d. is SU-9, about 119 cm wide and oriented N85W with dip 85N. The dike was offset by a south-dipping reverse fault or fracture, with a narrow band of dike in the fault. The country rock is the Sunapee Granite, a Late Devonian (?) 2-mica granite or monzonite of the “Concord granite” series.

The dike is an augite monchiquite of the Early Cretaceous NEQ province (McHone and Butler, 1984), not dated here but a similar dike on I-89 about 15 km to the south has a date of 95 ± 8 Ma (whole-rock K-Ar; McHone 1984). The dike also occurs in the high cut on the opposite (northeastern) side, but there it is split into two much narrower dikes, and not faulted. A dozen or so lamprophyre dikes crop out along I-89 in New Hampshire, including a cluster of them below the rest area not far to the northwest of Sunapee. The NH state police might well ticket you for stopping on this highway, so if you wish to visit one of the dikes, try the one along the N-entrance ramp at Exit 15 near Whaleback Ski Center.

An intense fracture zone about 5 m wide (Fig. 2) paralleled the Sunapee Dike, and crusts and flakes of bright yellow meta-autunite (hydrated calcium uranium phosphate) and green torbernite were prominent along surfaces in the granite fractures. The scintillometers we kept in our vehicles while cruising along the highway had their dials jump to the limit while buzzing merrily! The same dike splits and is much narrower on the east side road cut, where there are also fewer fractures and less U mineralization associated. We soon realized that groundwater was actively leaching uranium out of the relatively-radioactive 2-mica granite, and U-bearing minerals were precipitating at an oxidation interface near the top of the groundwater in the fractures. Several other, smaller road cuts in the area without dikes also showed uranium mineral concentrations in fractures near the tops of wet zones. In addition, aerial radiometric surveys showed elevated radioactivity over wetlands perched on this granite.

The Sunapee Granite at this location averages about 19 ppm U_3O_8, which is high although not extreme. At a talk at UNH many years ago, a respected local geologist proposed that the uranium is derived from the mantle via the dike, but this is very unlikely. Lamprophyres typically contain around 2-3 ppm U (diabase or dolerite is less than 1 ppm), and uranium minerals are not concentrated near dikes at most places in New England. The association of uranium mineralization with the interface of groundwater shows that its concentrations are recent and probably change with the groundwater levels through time. We have seen crusts of uraniferous minerals formed on low-grade sulfide mine tailings in wet areas, at copper prospects in northern Vermont dating to the 19^{th} century.

Local people were concerned during our field work (1979-80) about exploration and possible uranium mining in their neighborhood. It seemed to us that no mining is necessary: all you really need to do is circulate water lacking oxygen in the granite, then oxygenate it and watch the uranium minerals precipitate! Uranium is toxic in drinking water by itself, never mind radioactivity and radon by-product, so we should pay attention to this phenomenon (Hollocher and Yuskaitis, 1993).

The fault and fractures around the dike also deserve attention. Our interpretation is that the dike intruded a fracture of the pre-existing regional joint set, and given its heat, fluid pressure, and the brittle nature of the host rock, additional more closely-spaced joints formed along the dike. We see similar fracture patterns around some other dikes, although not usually so concentrated. The reverse fault then moved the dike and associated fractures according to a local compressional stress field. The offset must have occurred while the dike was still liquid, as shown by a narrow intrusion of it into the fault between dike segments. I regret not trying harder to document the actual offset direction prior to destruction of the cut, but usually a dike fracture should open in the direction of least compression, while maximum compression should be parallel to it. Thrusting indicates just the opposite here.

North Hartland Dike and Mantle Xenoliths

The North Hartland dike (Figs. 5 and 8) was first visited by Greg McHone in 1981 and is briefly described in Williams and McHone (1984) and McHone (1986). The dike is exposed in the spillway of the North Hartland Lake flood-control dam on the Ottauquechee River, and strikes N74°E with a variable dip near 68° SE. The main dike narrows from 55 cm to 33 cm or less higher in the cut, with the central 15 to 30 cm of the dike containing abundant xenoliths ranging in size up to 10 cm by 15 cm (Fig. 5). Thin dikelets or branches that lack xenoliths intrude nearby. The main dike is extremely fresh but shows numerous fractures and faults. The dike type is kaersutite-bearing olivine augite camptonite, and it has been dated via whole-rock K-Ar as 133 ± 6 Ma (Geochron Labs, unpub.).

Xenoliths include garnet-bearing quartz plagioclase gneiss, phyllite of the surrounding Gile Mountain Formation. There are abundant inclusions of spinel lherzolites and lesser amounts of dunite, harzburgite, and clinopyroxenite, as well as quartz plagioclase granulites and other xenoliths. The inclusions range up to fist-sized and are concentrated in bands through the middle part of the intrusion.

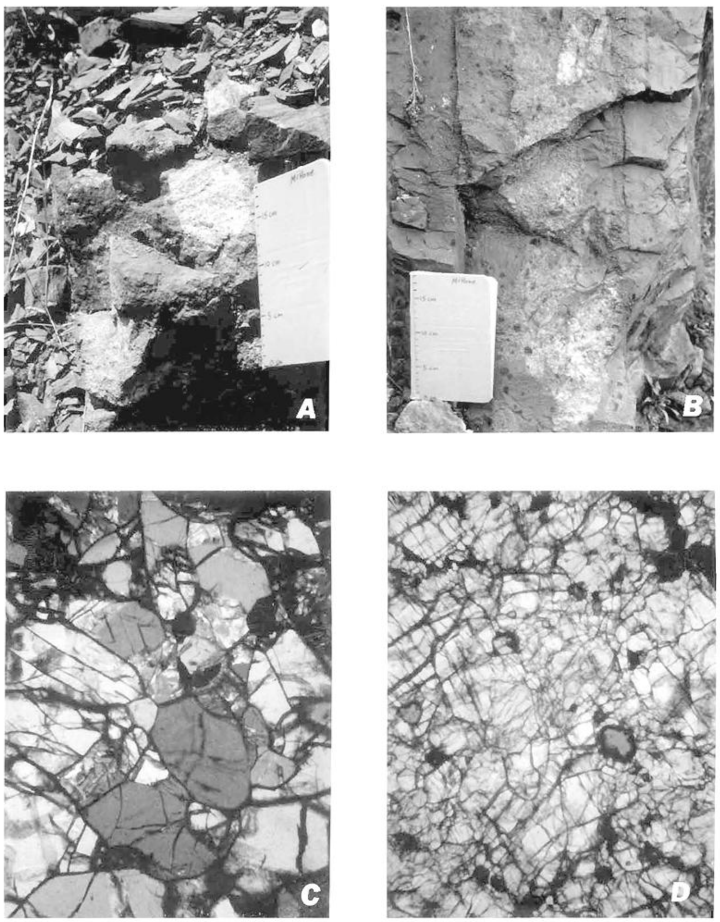


Figure 5 (left). North Hartland Dike and mantle inclusions. A and B: a variety of inclusions up to fist size crowd the center of the dike. C: photomicrograph of spinel lherzolite (peridotite). D: photomicrograph of spinel harzburgite (pyroxenite).

Electron microprobe analyses of mantle minerals from North Hartland include enstatite, diopside, low-Ti augite, Mg-rich olivine, brown chromian spinel, and rare phlogopite, with compositions that are generally comparable to mantle minerals from other New England and Quebec xenolithic lamprophyres (McHone, 1986).

Geothermometer calculations using the North Hartland analyses indicate equilibrium temperatures that are relatively low. Mineral temperatures calculated by methods after Gasparik and Newton (1984) and Wells (1977) range from 661° to 751° C, with lherzolites providing the higher temperatures (McHone, 1986). Equilibrium pressures calculated after O'Neill (1981) yield maximum values of about 13 kbars.

Other Mesozoic dikes in the Northeast contain high-grade metamorphic crustal inclusions, but dikes with ultramafic (mantle) xenoliths are very rare. The North Hartland ultramafic assemblages are in part like xenolith suites from lamprophyre dikes in Massachusetts (Ross and others, 1983) and Rhode Island (Leavy and Hermes, 1979), and from portions of the Ile Bizard intrusion near Montreal, Quebec (Raeside and Helmstaedt, 1982). A monchiquite dike with mantle and crustal xenoliths was also discovered in 1981 in Quebec (McHone, 1986; Trzcienski, 1989). Calculated temperatures and pressures, and studies of phase equilibria denote mantle conditions for the ultramafic assemblages. The inclusions demonstrate that lamprophyric magmas originate in the mantle, and fractionation or contamination processes that affect lamprophyres are minor enough to allow these less-stable mantle rocks to be preserved during rapid emplacement into the upper crust.

ACKNOWLEDGEMENTS

Peter Thompson suggested this trip and informed us about the excellent exposures of dikes behind the Upper Valley Aquatic Center in White River Junction. We appreciate permission from the UVAC for parking to examine them. We also appreciate permission from Heather Morse, Manager of North Hartland Lake (Army Corps of Engineers) to access the North Hartland Dam spillway. Our original work on the Hartland Dike was supported by N.S.F. Grant EAR82-l2496, and by grants from Sigma Xi, Standard Oil of California, and Geochron Laboratories.

ROAD LOG

From Mount Sunapee Ski Lodge, follow Rte. 103 (combined part-way with 11) west through Newport and Claremont, N.H., merging with Rte. 12 to cross the Connecticut River to Ascutney Village in Weathersfield, Vermont (intersection with Rte. 5). Pass through the village onto Rte. 131 and drive a short distance west to the underpass of I-91. For this route Google Maps gives the distance as 23.1 miles and about 47 minutes of driving from Mount Sunapee. If you are travelling by interstate highway, Stop 1 is at the end of the south-bound Exit 8 ramp off I-91.

Mileage

0.0 Park on the north side of Rte. 131 at the underpass, and walk a short distance to the road cut where the Exit 8 ramp from S-bound I-91 meets Rte. 131.

STOP 1. ASCUTNEY EXIT 8 DIKE (25 MINUTES) Watch the traffic! The augite monchiquite dike (CL-4) in the road cut on the west side of the ramp is big for a lamprophyre at 215 cm wide, strike N61W dip 5 SW (Fig. 5). Thin sections show beautiful stained-glass views due to the large mafic minerals. You might have seen it as Sample #2 in Forbes-Robertson educational rock collections. Like all monchiquites it is rich in mafic minerals with little feldspar or felsic analcime, making it a heavy and dark rock. The dike intrudes Late Silurian/Early Devonian Waits River Formation, not far west of the border structures with New Hampshire (dike is in the center of Fig. 6).

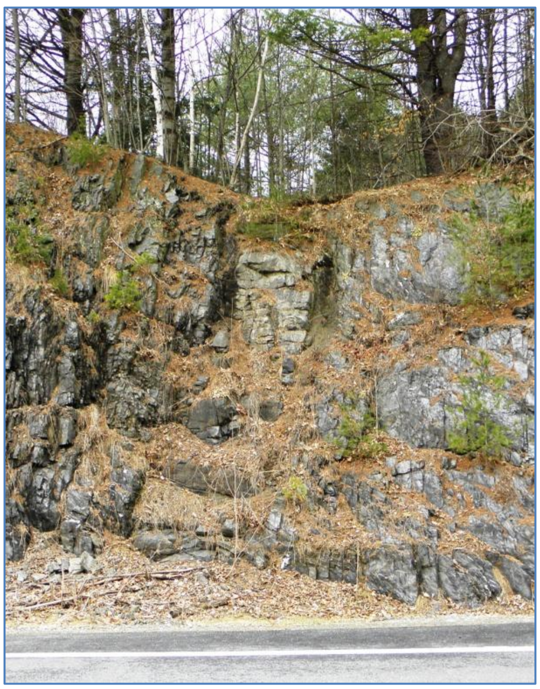


Figure 6 (left). Monchiquite dike CL-4 near Ascutney Village.

There are a few fractures or joints paralleling the dike. Despite its very mafic composition the dike was probably quite fluid and so intruded one of the local regional joints. Additional joints along the dike may have developed from the hydraulic pressure in combination with stress from heat, with the dike fracture initially expanding and then contracting when the dike magma ceased to flow and the pressure reduced.

Unlike camptonite, dikes of monchiquite are not evenly distributed across northern New England. There are definite zones or clusters where they occur, with many in the central Lake Champlain Valley, and others nearby to some of the Cretaceous plutonic complexes such as the Monteregian Hills and Ascutney Mountain. A few are found along the Green Mountain Anticlinorium, and a group occurs near Concord, N.H., but there are large areas with none known.

This distribution is similar to the felsic (trachyte or bostonite) dikes of the NEQ province, and it helped us to formulate a model in which camptonite-based magma that collects in magma chambers in the lower lithosphere splits through a liquid-immiscibility mechanism into felsic and extra-mafic portions. These then fractionate into the bi-model syenite-gabbro association that is common in alkalic plutons, including Ascutney Mountain. Evidence includes the compositions of ocelli in camptonite, which are eye-like segregations of felsic minerals that appear to be developed from a co-liquid but volatile-rich silicic magma. We discussed this model in a previous NEIGC field guide (McHone and McHone, 1999) if you are interested.

0.1 Go east under the overpass and turn left (north) onto the entrance ramp onto North I-89. Travel to Exit 9 (8.9 miles).

On the way you will pass several small lamprophyre dikes in fine road cuts along the west side of I-91 (not stops), which may be hard to see. Assuming you have permission to stop on the interstate, you need to be traveling south to visit them.

One of these lamprophyre dikes not far north of Ascutney Mountain shows an interesting offset, with leading fingers of dike magma on opposite sides (Fig. 7). The offset is probably syn-intrusional, not a later fault, and magma flowing in the dike segments must connect better in a horizontal sense rather than vertically.

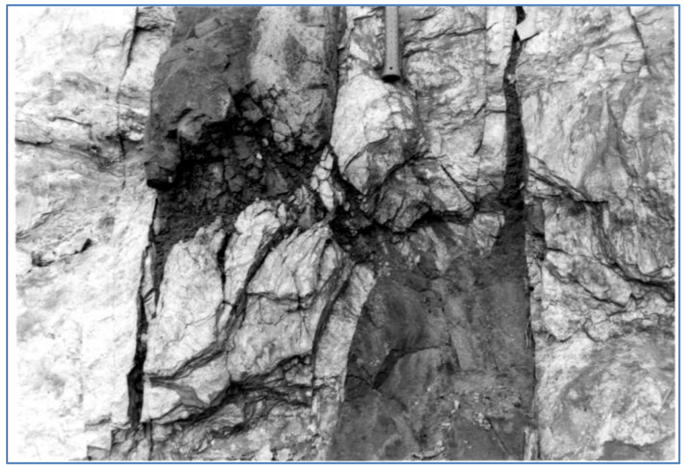


Figure 7 (right). Dike CL-5, in a road cut on the west side of South I-89 near Ascutney Mountain. Note the rock hammer handle for scale.

9.0 Take Exit 9 to Rte. 5 North, drive through Hartland Village and continue north on Rte. 5. After crossing the Ottauquechee River (at 6.6 miles from the exit) watch for the gate on the left (west) side of Rte. 5.

15.8 Park where you can along the shoulder of Rte. 5, off the pavement, and watch for traffic! Walk around the gate and up a gravel access road to the spillway for the North Hartland Dam.

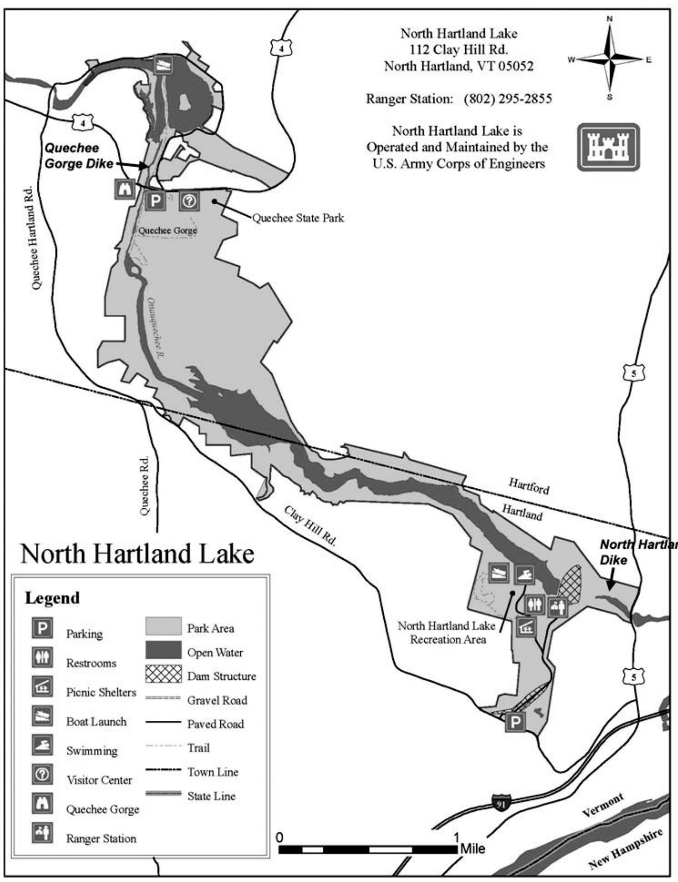


Figure 8 (left). Map of North Hartland Lake and Quechee Gorge parks, showing locations of dikes at stops 2 and 3. Labels are added to the map. Source:http://www.nae.usace.army.mil/ recreati/nhl/nhlmaps.htm

STOP 2. NORTH HARTLAND DIKE (50 MINUTES). Walk a quarter mile or so up the gravel road and spillway cut. This is a security-sensitive area and we are here by special permission. Please do not photograph the dam and other facilities, only the rock face and dike. TAKE NO SAMPLES.

The dike (i.d. HN-15, N74E, 68SE, 3-49 cm wide) is in phyllite of the Meetinghouse Slate member of the Devonian Gile Mountain Formation, but Ordovician Ammonoosuc Volcanics is mapped along the access road below the spillway. Thus we are close to the Monroe Fault, or the dividing line between the Vermont and New Hampshire sequences.

As we walk up the spillway, observe the deformation in this brittle, slippery phyllite. We will discuss the mechanics of xenolith transportation, dike intrusion, and faulting.

Return to your vehicle and carefully turn around to head south on Rte. 5 (watch for traffic!). It is about 0.5 miles to a right turn onto Clay Hill Road (see map).

16.6 Turn right (west) onto Clay Hill Road.

17.7 Continue past the gate to the ranger station and picnic area for Hartland Lake. In season they are open M-F 7:00 AM to 3:30 PM, and you can visit the manager to seek permission to access the spillway. Or if not, perhaps they will allow you to walk out on the top of the massive dam, where there were large pieces of xenolithic dike material. You may have to be very persuasive to take some away with you, however!

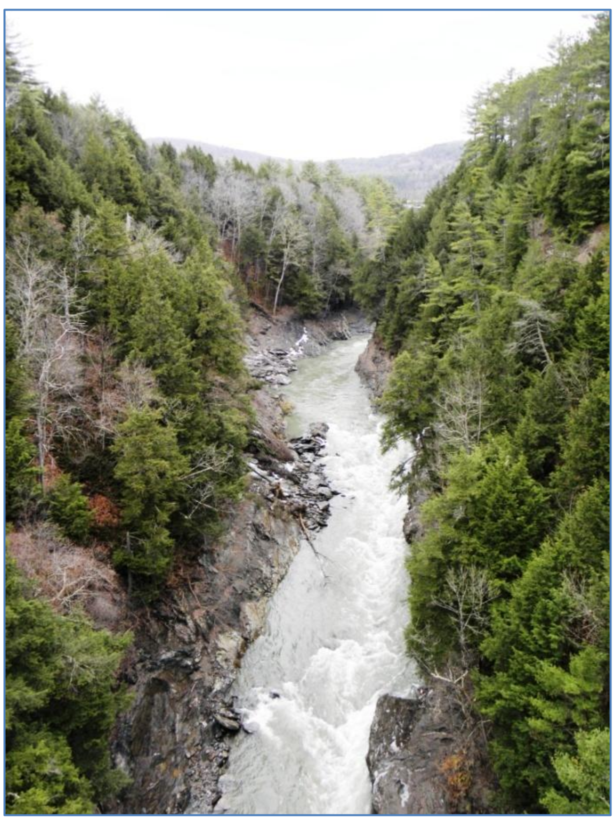
20.7 Turn right onto Quechee-Hartland Road. Travel north to Rte. 4.

22.8 Turn right (east) at the blinking light onto Rte. 4.

23.9 Cross the bridge over Quechee Gorge and turn right into the parking lot of the Visitors Center. There are rest rooms inside, and across the road are restaurants and shops where you can buy lunch. If it is early enough we will walk directly to the Quechee Gorge Dike and eat lunch afterward, or if we are running late we can eat first.

STOP 3. QUECHEE GORGE DIKE (90 MINUTES) Cross the bridge on the north side on foot and observe the dike beneath you. Then follow the trail northward along the western side of the gorge about ½ km or so, turning to descend a branching trail to the river at the far location in Figure 9. It is much better to visit when the river is low. The dike is about 110 cm wide, strike N10E, dip 68 E. This is a good augite camptonite.

The Quechee Gorge dike was first mentioned by James Kemp (1894) in a very brief description based on samples sent to him by C. H. Hitchcock. Kemp identified it as camptonite but without any discussion. Like most local travelers we only knew Quechee Gorge from the bridge, and we had to descend to the river to actually find the dike. However, once you know it is there, the dike can be recognized at several places along the gorge and under the bridge, especially at low water. Rather than climbing down a steep trail near the campground, it is much easier to hike north along the western side from the highway and then down to the river farther upstream (Fig. 9).



This part of the gorge is in micaceous quartzite or meta-pelite of the Devonian Gile Mountain Formation. The gorge is very straight at about 10 degrees east of north for a kilometer or so. The dike follows the western river bank for most of its length, which is not likely a coincidence, thus the short note in the Vermont Geological Society newsletter (McHone, 1981) about how the gorge is eroded from a fracture system developed along and because of the dike. The Flume in the White Mountains of New Hampshire developed the same way, but here it is much bigger!

Figure 9 (left). Quechee Gorge north of the Rte. 4 highway bridge. The dike enters the bank from the river at the far end of this section, but at times of low water it can be seen along the western side of the river in both directions from the bridge, dipping eastward within the rock cleavage.

LUNCH AT QUECHEE GORGE TOURIST PLAZA. Please be ready to leave in 30 minutes.

Turn right onto Rte. 4 and drive a few miles to the entrance onto South I-89.

27.1 Turn right onto South I-89 (exit 1).

30.1 Take the exit for I-91 North. As you merge onto I-91, stay in the right lane and immediately take the first exit.

30.6 Right at Exit 11- Route 5/White River Junction. At the bottom of the ramp take a left onto Route 5 South.

31.2 After passing under the highway overpass, make your first left on Arboretum Lane. The Upper Valley Aquatic Center is straight ahead.

31.6 Drive around the UVAC and park in the upper back area near the quarry wall.

STOP 4. UPPER VALLEY AQUATIC CENTER DIKES (30 MINUTES). Stay inside the fence.

The quarry is in meta-volcanics of the Ordovician Ammonoosuc Formation, near the Ammonoosuc and Monroe Faults. As in the interstate highway intersection a few hundred meters to the east, slickensided fault surfaces are abundant, some of which cut mafic dikes that we think are probably Early Jurassic alkali diabase dikes. However, the dikes are rather altered by post-magmatic hydrothermal effects, which make their identity somewhat uncertain – they also resemble camptonites of the NEQ province. Which age group they are in is important for the history of the fault activity that affects the dikes, but their alteration is a problem for radiometric determinations.

Figure 10 (left). Branching dikes at the western corner of the quarry wall behind the Upper Valley Aquatic Center. Many of the schistose rock surfaces appear to have slickensides, with some faults cutting dikes.

Faults in the HN-5 and HN-9 dikes in the intersection (Table 2) are in the same style as surfaces here, but as you may note it can be hard to distinguish dike surfaces from host rock cleavage in the rusty gray and weathered areas. We need to spend more time making a careful examination and map of the rock faces to draw better conclusions. Or perhaps you might volunteer for this work? It is important to determine and measure as many fault offsets as we can, to provide evidence for the sense of brittle movement of the major boundary between the New Hampshire and Vermont sequences.

If your field day has ended, return to I-91 and other intersections with I-89 or local highways to head to your destination. Or, if you wish to visit Stop 5:

32.6 Enter ramp for South I-91.

33.0 Exit onto South I-89.

40.2 Take Exit 17, and turn onto Rte. 4 heading back toward Lebanon.

Figure 11 (right). Alkali diabase dike MS-3, along the Exit 17 South I-89 entrance ramp from Rte. 4.

40.9 At the entrance ramp to South I-89 turn around on Rte. 4 to park on the south side, where there is a wide shoulder. If you brave the state police you might park along the entrance ramp (off the pavement next to where this dike may or may not still be!), but it is probably safer to park along Rte. 4 before entering the ramp and walk up along the west side for a hundred or so meters.

STOP 5. (OPTIONAL) EXIT 17 DIKE (20 MINUTES). In early July 2012 the highway department was busy cutting back this road cut, so on the assumption that the exposure may no longer exist, we have made it purely optional rather than part of the field trip.

This is an example of a New Hampshire-type alkali diabase dike (our MS-3), containing some biotite but not quite a camptonite or spessartite. There are many like it associated with the White Mountain Magma Series, but here we are pretty far from the large Jurassic plutons. The dike cuts Ammonoosuc Volcanics with a strike of N46E, dip 72NW, width 248 cm. The dike has an unpublished whole-rock K-Ar date of 181±7 Ma (Geochron Labs), with no chemistry, regretfully. Note how massive it appears, without the brown surface or fine-granular texture common for lamprophyres.

END OF TRIP.

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