Smith-Amherst Mineralogy Field Trip
to the Adirondack Mountains

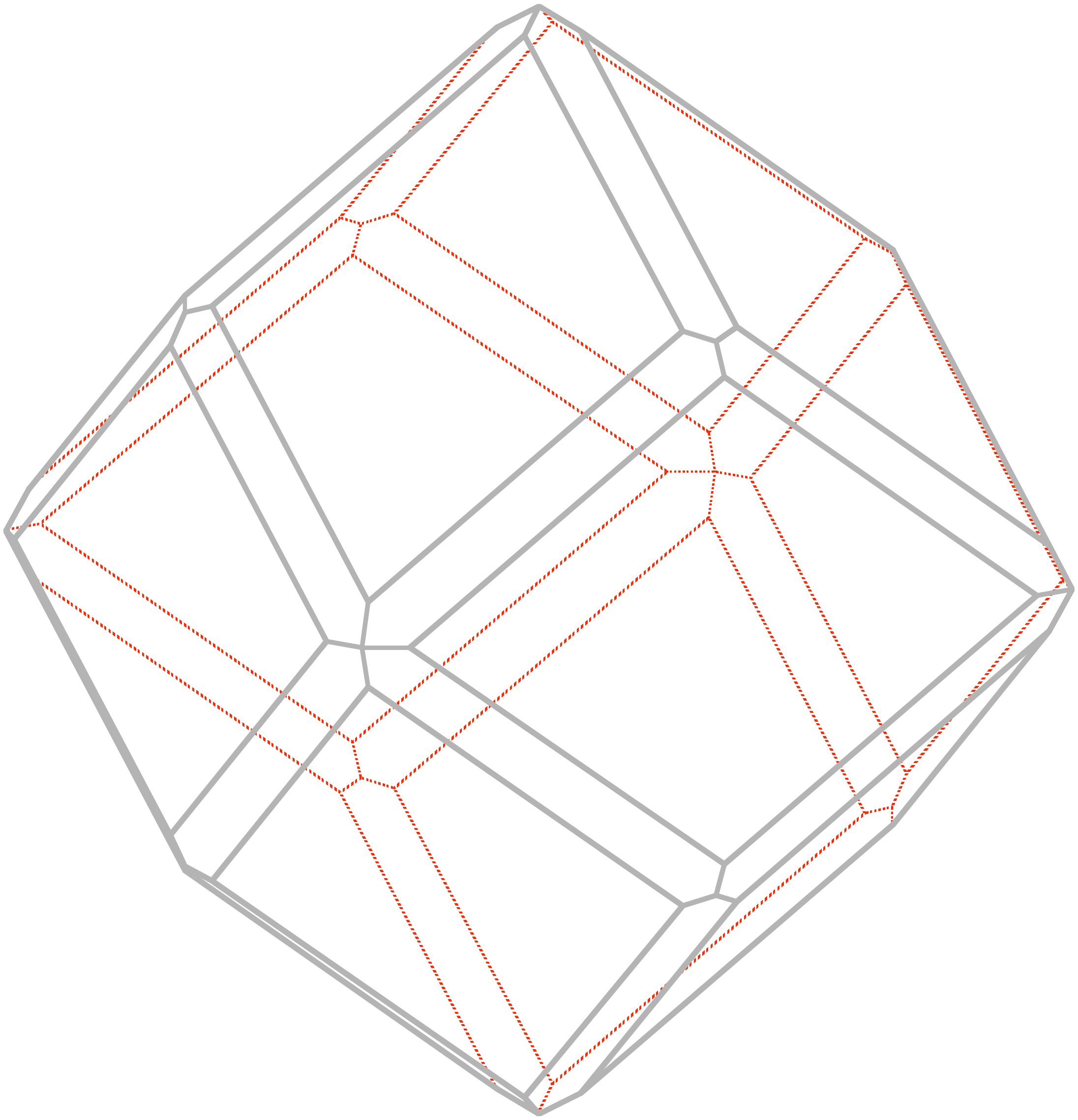
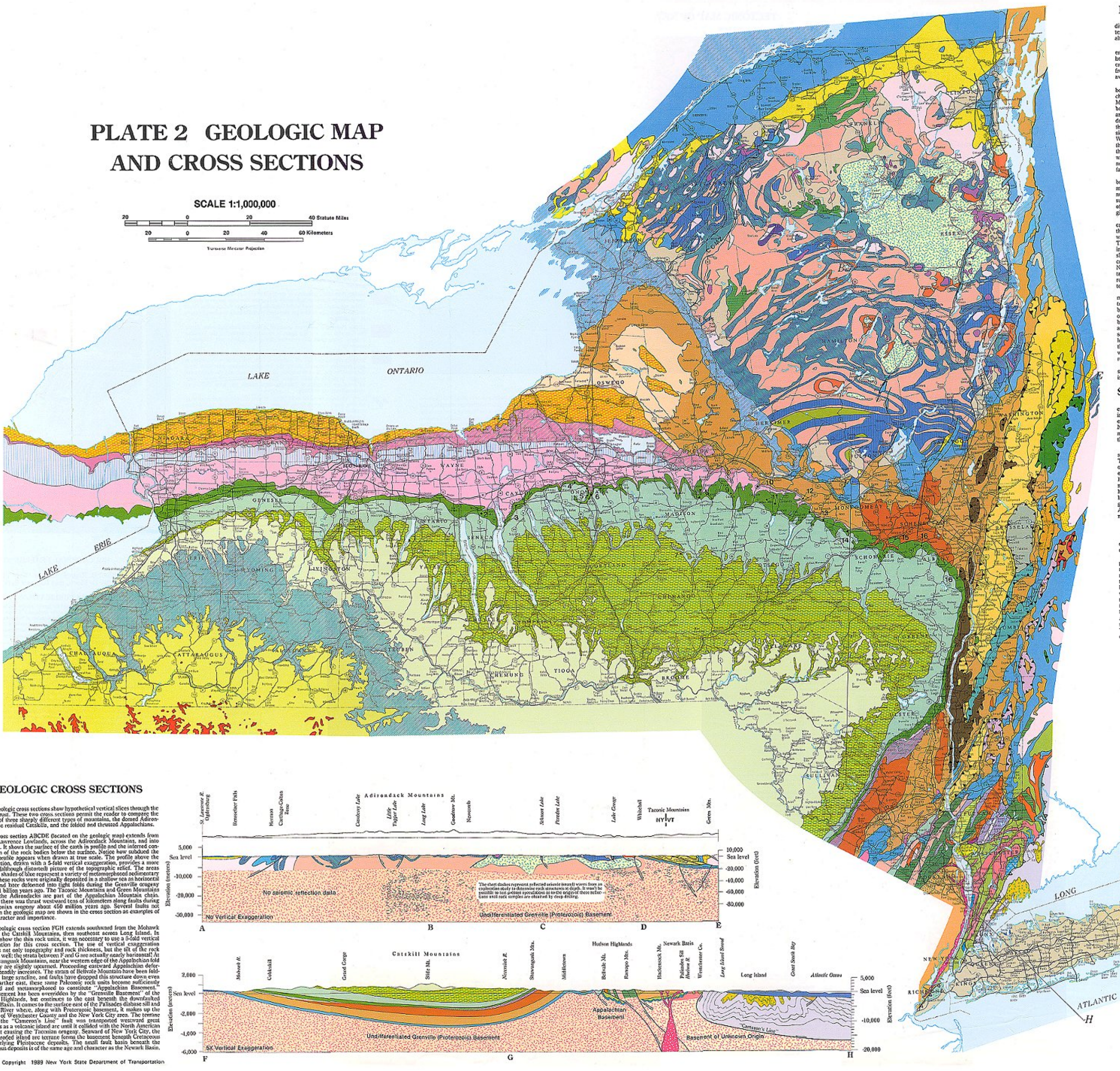


PLATE 2 GEOLOGIC MAP AND CROSS SECTIONS



BEDROCK GEOLOGY OF NEW YORK

The crust of the earth is solid rock, tens of kilometers thick, made up of individual rock bodies that vary in size, shape, orientation, composition, color, and texture. Together they make up the bedrock, which is present everywhere, although commonly masked by surficial deposits.

The bedrock geologic map gives a vertical view of the pattern made by the eroded edges and surfaces of the rock bodies that crop out in the State. It is, however, only a two-dimensional view of three-dimensional rock bodies. The cross sections below the map show samples of the third dimension as inferred from the surface configuration of rock bodies and other information that may be available from drill holes or geophysical measurements.

Map patterns result from the intersection of topography and individual rock bodies. Most rock bodies are originally tabular and horizontal, but deformation changes their orientation and shape by tilting, folding, crumpling, and breaking. Map patterns can tell us much about the three-dimensional configuration of bedrock in different regions. For example, the rock bodies in western New York are layers of sedimentary rock, of greatly different thicknesses, that are tilted down to the south less than 1 degree. The broad bands on the map in that area are the patterns made by stacked layers that have been beveled at a low angle by erosion. (Visualize a layer cake sliced at a low angle instead of the usual vertical.) Widths of outcrop bands are controlled by the thicknesses of individual map units, the topography, and the low dip. Stream valleys account for the jagged details in the pattern. Steeply dipping faults are omitted from the geologic map except where they separate rock bodies of greatly different ages. This avoids unnecessary congestion on the map, especially within the Adirondacks where such faults abound.

In the Adirondack Mountains the map pattern shows once-tabular rock bodies now swept into broad folds. This deformed-rock pattern is typical of highly metamorphosed "basement" rock. One can easily visualize this rock pattern continuing in the basement as it passes beneath the blanket of sedimentary strata that surrounds the Adirondacks. The pattern of small blocks along the eastern border of the Adirondacks results from faulting that dropped crustal blocks down into a giant staircase.

The Taconic Mountains east of the Hudson River Valley are huge slices of crust that were thrust into that area from the east. The heavy toothed lines show the edges of these thrust sheets. The earth's crust in this region was "telescoped" when a volcanic island arc collided with the edge of the continent, causing the Taconian orogeny. This collision compressed the layered rock and sediment of the intervening sea, thrusting them westward onto the continent as huge, stacked slices. The slices, which generally dipped east in a shingled arrangement, were contorted considerably in the process. When completed, the stack extended from New England past the western edge of the Hudson Valley. In the Catskill Mountains, the western edge of this transported rock remains buried beneath Devonian rock. Erosion has reduced the original thrust sheets to patches, creating windows to the rock beneath.

The legend on the facing page shows the formations and rock types in each map unit. The legend has two major parts based on divisions of geologic time, Proterozoic and Paleozoic-Mesozoic. Highly deformed Proterozoic rock bodies of the basement are buried beneath younger Paleozoic rock in most of the State, but crop out in the Adirondacks and the Hudson Highlands. Southeast of the Highlands, basement relationships become more complex as one approaches the deformed and metamorphosed root zone of the ancestral Appalachian Mountains (see cross section FGH beneath the geologic map). The Paleozoic-Mesozoic part of the legend applies to the wide expanse of sedimentary rock formations that blanket the State west of the Hudson River and south of the Adirondacks. The blank areas with yellow tint represent gaps in the rock record—geologic times not recorded by rock because of erosion or non-deposition.

Surficial material is ignored on generalized bedrock geologic maps, but it is shown here in several areas of the Adirondacks and over all of Long Island, where is it so thick that it masks all clues to the bedrock geology.

SURFICIAL GEOLOGY OF NEW YORK

Bedrock generally is covered by a skin of soil and other loose material, especially in regions with humid climates. This cover material results as weathering breaks down the surface rock. The loose materials may remain in place or be eroded, transported, and deposited by water, wind, or glacial ice. In 90 percent of New York State, bedrock is buried by surficial deposits that are more than one meter thick. Most of these deposits were left by a continental glacier—an ice sheet that was perhaps 2 km thick.

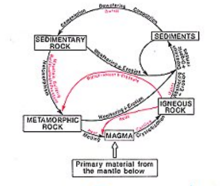
Till is the most abundant glacial deposit. It is an unsorted mixture of mud, sand, gravel, cobbles, and boulders that the glacier spread over the countryside. Till can be up to 50 meters thick. It is generally thickest in valleys and thinnest over highlands. *Moraines* are elongate ridges or strings of hills that formed at the edge of the glacier and are composed of sand, gravel, or till. The Ronkonkoma and Harbor Hill moraines on Long Island dominate that landscape. The Valley Heads moraine dams the south ends of the Finger Lakes. *Glacial lake beds* are broad horizontal layers of mud (deep water) and sand (shore zone) that were deposited in lakes that formed in front of the glacier as the ice melted. *Outwash* is sand and gravel deposited by meltwater streams that flowed from the front of the glacier. All of these kinds of deposits have a wide range of thicknesses. In places, they may be piled one on top of the other.

ROCK FORMING PROCESSES

The earth's crust is of two major types, continental (35 km thick) and oceanic (10 km thick). Continental crust is less dense than oceanic crust, which causes the continents to stand higher than the ocean floors.

Three major classes of rock make up the earth's crust: igneous, metamorphic, and sedimentary. Continental crust is divided into crystalline "basement" rock and overlying layers of sedimentary rock or layered volcanic rock. The basement is a complex of metamorphic and igneous rock bodies that were generated in the roots of mountains. These record long, repeated cycles of submergence; burial by sedimentation; mountain-building with metamorphism, igneous intrusion, and volcanism; and uplift and erosion. Sedimentary rock blankets the basement over three quarters of the earth's continental area. This blanket ranges in thickness from a feather edge to more than 14 km. It includes many individual layers that began as widespread horizontal accumulations of sediment such as sand and mud. As sediment piles up, the lower part is compressed under the load. Water is squeezed out of the pores, and eventually the sediment is cemented into rock. These processes and cycles are summarized by the Rock Cycle diagram below.

ROCK CYCLE in EARTH'S CRUST



GEOLOGIC CROSS SECTIONS

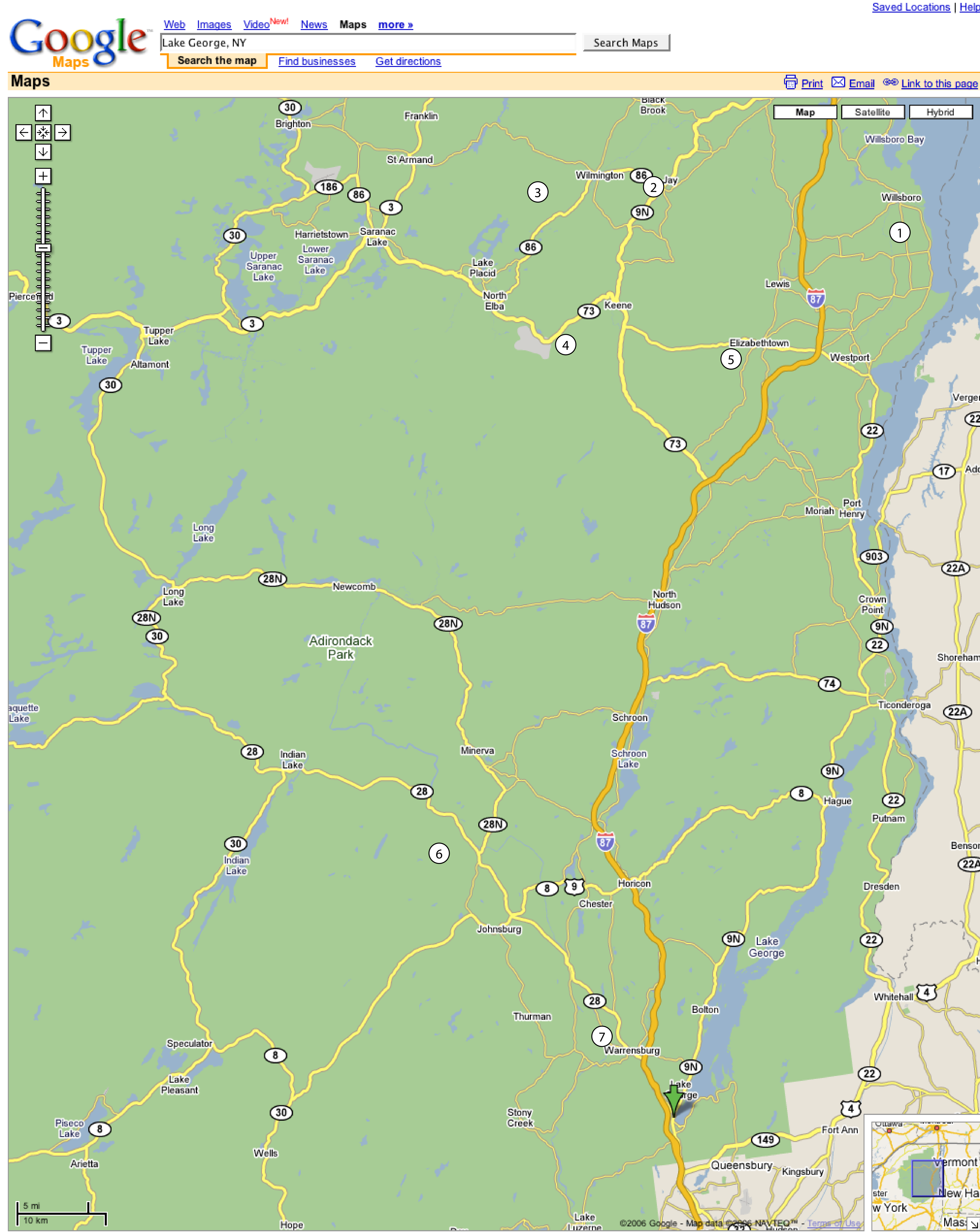
Geologic cross sections show hypothetical vertical slices through the earth's crust. These two cross sections permit the reader to compare the geology of three sharply different types of mountains, the domed Adirondacks, the residual Catskills, and the folded and thrusted Appalachians.

Cross section ABCDE (located on the geologic map) extends from the St. Lawrence Lowlands, across the Adirondack Mountains, and into Vermont. It shows the surface of the earth in profile and the inferred configuration of the rock bodies below the surface. Notice how subdued the surface profile appears when drawn at true scale. The profile above the cross section, drawn with a 5-fold vertical exaggeration, provides a more familiar (although distorted) picture of the topographic relief. The areas shown in shades of blue represent a variety of metamorphosed sedimentary rocks. These rocks were originally deposited in a shallow sea as horizontal layers, and later deformed into tight folds during the Grenville orogeny about 1.1 billion years ago. The Taconic Mountains and Green Mountains east of the Adirondacks are part of the Appalachian Mountain chain. Bedrock there was thrust westward tens of kilometers along faults during the Taconian orogeny about 450 million years ago. Several faults not shown on the geologic map are shown in the cross section as examples of their character and importance.

Geologic cross section FGH extends southward from the Mohawk River to the Catskill Mountains, then southeast across Long Island. In order to show the thin rock units, it was necessary to use a 5-fold vertical exaggeration for this cross section. The use of vertical exaggeration amplifies not only topography and rock thickness, but the tilt of the rock layers as well; the strata between F and G are actually nearly horizontal! At the Shawangunk Mountains, near the western edge of the Appalachian fold belt, they are slightly upturned. Proceeding eastward Appalachian deformation steadily increases. The strata of Bellvale Mountain have been folded into a large syncline, and faults have dropped this structure down even more. Farther east, these same Paleozoic rock units become sufficiently deformed and metamorphosed to constitute "Appalachian Basement." This basement has been overridden by the "Grenville Basement" of the Hudson Highlands, but continues to the east beneath the downfaulted Newark Basin. It comes to the surface east of the Palisades diabase sill and Hudson River where, along with Proterozoic basement, it makes up the bedrock of Westchester County and the New York City area. The terrane east of the "Cameron's Line" fault was transported westward great distances as a volcanic island arc until it collided with the North American continent causing the Taconian orogeny. Seaward of New York City, the deeply eroded island arc terrane forms the basement beneath Cretaceous and overlying Pleistocene deposits. The small fault basin beneath the Cretaceous deposits is of the same age and character as the Newark Basin.

Explanation for the numbers that appear on the map

1	Western limit of Tully Limestone
2	Western limit of Helderberg Group
3,4,5,6,8,11,13	Patches of Oriskany Sandstone
7	Eastern limit of Tully Limestone
9	Western limit of Esopus, Carlisle Center, and Schoharie Formations
10	Eastern limit of Lockport Dolostone
12	Eastern limit of Clinton Group
14	Western limit of continuous Oriskany Sandstone
15	Eastern limit of Cobleskill Limestone
16-16	Zone of change from Oriskany Sandstone to Glenerie Limestone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Black Brook
Franklin
Brighton
St Armand
Wilmington
Jay
Willsboro Bay
Willsboro
Harrietstown
Saranac Lake
Upper Saranac Lake
Lower Saranac Lake
Lake Placid
North Elba
Keene
Lewis
Elizabethtown
Westport
Piercefield
Tupper Lake
Altamont
Vergennes
Addison
Moriah
Port Henry
Long Lake
Newcomb
Crown Point
North Hudson
Adirondack Park
Shoreham
Ticonderoga
Raquette Lake
Schroon
Schroon Lake
Indian Lake
Minerva
Hague
Putnam
Benson
Horicon
Chester
Johnsburg
Dresden
Lake George
Thurman
Bolton
Whitehall
Speculator
Warrensburg
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Lake George
Stony Creek
Piseco Lake
Fort Ann
Arietta
Wells
Queensbury
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Hope
Lake Luzerne
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5 mi
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Ottawa
Montreal
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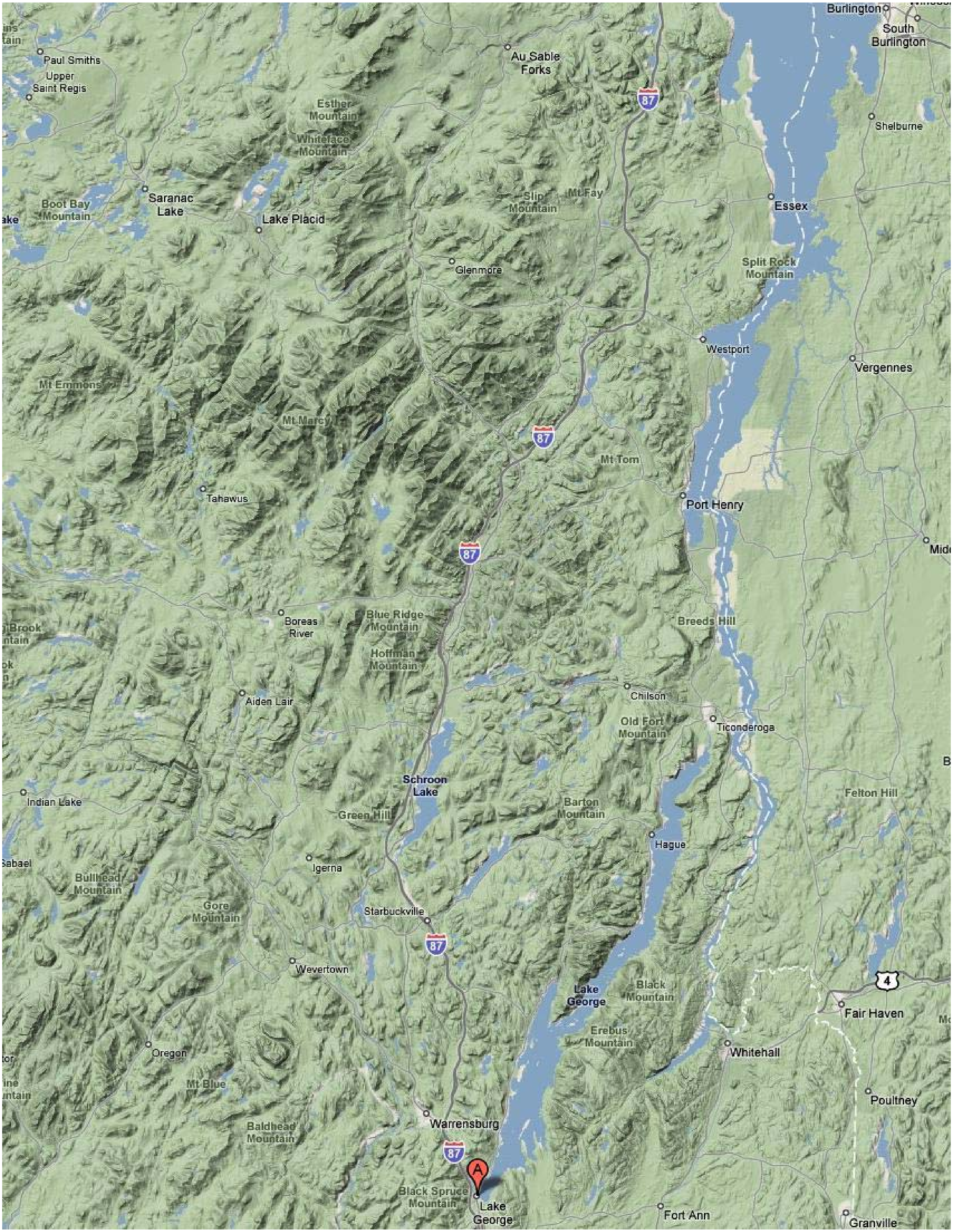
Burlington
South Burlington
Paul Smiths
Upper Saint Regis
Au Sable Forks
87
Esther Mountain
Whiteface Mountain
Shelburne
Saranac Lake
Boot Bay Mountain
Lake Placid
Slip Mountain
Mt Fay
Essex
Glenmore
Split Rock Mountain
Westport
Vergennes
Mt Emmons
Mt Marcy
87
Mt Tom
Tahawus
Port Henry
87
Boreas River
Blue Ridge Mountain
Breeds Hill
Hoffman Mountain
Chilson
Aiden Lair
Old Fort Mountain
Ticonderoga
Schroon Lake
Indian Lake
Barton Mountain
Felton Hill
Green Hill
Hague
Igerna
Bullhead Mountain
Gore Mountain
Starbuckville
87
Wevertown
Lake George
Black Mountain
4
Fair Haven
Erebus Mountain
Whitehall
Oregon
Mt Blue
Poultney
Warrensburg
Baldhead Mountain
87
A
Black Spruce Mountain
Lake George
Fort Ann
Granville

STOP A-1: WILLSBORO WOLLASTONITE MINE

Description modified from Bohlen, McLelland, Valley, and Chiarenzelli (1992).

The Willsboro underground mine (now abandoned) is situated near the eastern end of a belt of metasedimentary rocks that can be traced west and then southwest for almost 15 km, close to or at the contact of the Westport anorthosite dome, to the Lewis mine at its western end.

The lowermost rock unit at the Willsboro mine is anorthositic gneiss of the Westport Dome. It contains over 90% plagioclase (An_{50}), with large (>5 cm) dark bluish plagioclase megacrysts in a lighter bluish-gray matrix. At the mine, the anorthosite is overlain locally by a mafic gneiss a few tens of meters thick; this unit is absent further west. Above the mafic gneiss is the wollastonite ore, a coarse-grained (1-5 cm) rock. In spite of tight isoclinal folding, the foliation is subdued and is defined by oriented wollastonite grains and layers and streaks of dark minerals. The ore consists of only three minerals: wollastonite, grandite garnet (Grs_{10-90}), and Di-Hd clinopyroxene. Thick, skarn-like masses of grossular and pyroxene are found along the edges or occasionally within the unit. The mineralogy and geologic setting favor an origin by contact metamorphism of siliceous carbonate rocks at the time of anorthosite intrusion. The fact that calcite and quartz are ordinarily absent in this high-variance assemblage suggests that metasomatism played a major role in the ore forming process (Buddington, 1939; DeRudder, 1962). Prior to 1982 it was widely accepted that the anorthosite intruded at depths of 20-25 km during Grenville regional metamorphism.

Above the wollastonite are thin units of anorthositic, granitic, mafic and calcsilicate gneisses, and amphibolites. In some of these exposures we find masses of nearly pure garnet rock suggesting repetition of the ore unit. Observe that wollastonite weathers rapidly and is rarely seen at the surface, locally leaving garnetite or diopsidite "skarns" as the sole evidence of its presence.

The uppermost unit is a thick, sill-like body of gabbroic anorthosite gneiss . This extends the entire length of the metasedimentary belt and differs from the anorthosite of the Westport Dome both in composition and texture. The contacts of this unit with metasedimentary rocks are not well exposed here, but elsewhere they are marked by pyroxene-rich skarns. As we return to the mine we will examine a metagabbro unit and its contacts with enclosing metasedimentary rocks.

Valley and O'Neil (1982, 1984) and Valley (1985) have reported anomalously low $\delta^{18}O$ (-1.3 to 3.1; up to 20 permil lower than typical Adirondack marbles) in the wollastonite ore within 125 m of the anorthosite contacts, as well as extremely sharp $\delta^{18}O$ gradients between the wollastonite and the surrounding rocks. The low $\delta^{18}O$ values cannot be explained solely by devolatilization reactions (Valley, 1986) and result from deep circulation of heated meteoric waters along fractures at the time of anorthosite intrusion. Because such fluids would be at hydrostatic pressure, they should not penetrate a ductile metamorphic environment where fluids are at lithostatic pressure. This suggests that skarn formation occurred at shallow depths (<10 km) relative to granulite facies metamorphism. These stable isotope data were the first quantitative evidence for shallow intrusion of anorthosite within the Grenville Province. The origin of the sharp gradients is enigmatic; they may represent pre-granulite facies faults or shears, but their preservation through granulite facies metamorphism indicates that there was no significant fluid movement across strike during the regional metamorphism.

STOP A-2: EXPOSURES IN THE EAST BRANCH OF THE AUSABLE RIVER BY THE COVERED BRIDGE IN JAY

Description modified from Bohlen, McLelland, Valley, and Chiarenzelli (1992).

Upon parking in southernmost area on the southeast side of the river, walk a few tens of feet farther south along the paved road. At the sharp bend in road there is a low, polished outcrop that exposes two exceptional examples of rafts of coarse, blue-gray andesine anorthosite of the Marcy facies. The more southerly of these is enveloped in medium-grained gabbro similar to the xenolith-bearing, gabbroic facies on Giant Mountain. The gabbro is, in turn, surrounded by a fine-grained anorthosite. The northern raft of Marcy anorthosite lacks the rim of gabbro and is directly surrounded by the white, fine-grained anorthosite. The northern raft also contains a giant pyroxene whose edges show subophitic relationships with plagioclase.

Within the river there occurs a wide area of water-swept exposures of white, fine-grained, and highly layered anorthosite containing a few remnant blue-gray andesines as well as a few blocks of subophitic gabbro. The exposures are disrupted by two types of dikes: 1) late unmetamorphosed (Phanerozoic?) diabase paralleling the river, and 2) irregular, pyroxene-rich dikes and veins that trend mainly N-S and E-W but show other orientations and right angle turns as well. Some of the dikes are 15-20 cm wide but most fall into the 2-5 cm range. Both sharp and gradational contacts exist. Several of the dikes intrude along zones of mafic mylonite that may be of the same composition as the dikes themselves.

Mineralogically the dikes consist of coarse, emerald-green clinopyroxene and Fe, Ti-oxide. Some dikes also contain small quantities of plagioclase, garnet, and apatite. The apatite-free dikes contain very Mg-rich clinopyroxene (X_{Mg} ~80) while the apatite-bearing ones are less magnesium (X_{Mg} ~65). The key to understanding these dikes is to note that some exhibit comb structure defined by pyroxene and plagioclase crystals growing perpendicular to dike walls. Thus texture is diagnostic of growth from a fluid and provides compelling evidence that the dikes were intruded as liquid-rich magma. Preliminary experimental work by D. Lindsley (personal communication) indicates that representative dike material reaches its liquidus at 1200 ˚C (max).

It is suggested that these pyroxene-rich, and sometimes apatite-bearing, dikes represent immiscible silicate fractions complementary to magnetite-ilmenite deposits. Emplacement may have occurred when jostling about of essentially congealed plagioclase cumulates resulted in fracturing and the development of large blocks whose shifting provided passageways along which pyroxene-oxide magmas could be filter pressed. Depending on the batch of magma tapped, the intruding material would vary from Mg-rich to Fe-rich with apatite. Some dikes may have been cumulate-rich.

Dikes of the sort exposed in the river at Jay are common throughout the Marcy anorthosite massif, and their presence indicates a substantial, but small, amount of mafic material - and possibly mafic cumulate - in the massif. Invariably these dikes consist of green clinopyroxene and Fe, Ti-oxide, and it is common to find the silicate and oxide phases physically separated within the same vein. It is possible that, where this occurs, it reflects liquid immiscibility operating on late-stage interstitial fractions which are filter-pressed into veins.

STOP A-3: TOP OF WHITEFACE MOUNTAIN

Description modified from Bohlen, McLelland, Valley, and Chiarenzelli (1992).

The rocks at the summit of Whiteface Mountain represent the type locality for the Whiteface type, or facies, of anorthosite. This is typically finer-grained, garnetiferous, and somewhat more gabbroic than the Marcy facies. In general the Whiteface facies exhibits a chalky-white color and commonly contains significant quantities of black hornblende.

As originally defined, the Whiteface facies was considered to be the border facies of the anorthosite massif with the coarse, less gabbroic Marcy facies restricted to the core. As previously noted, the actual distribution is not nearly so regular and examples of Whiteface facies are found throughout the massif and range in composition from gabbroic anorthosite to anorthosite. The important thing to retain from the nomenclature is that the Whiteface type is a clearly intrusive rock, and its more gabbroic varieties represent a good starting material for other rock types in the anorthosite massif. As discussed previously, Whiteface anorthositic gabbro was probably emplaced as a plagioclase-rich crystal mush that had evolved from gabbroic precursors fractionated at the crust-mantle boundary.

STOP A-4: CASCADE SLIDE, MARBLE XENOLITH IN ANORTHOSITE

Description from Bohlen, McLelland, Valley, and Chiarenzelli (1992).

Walk south up talus slope to remains of a dam at the base of a waterfall. From this point, climb the steep gully to the east of the falls. Use extreme caution! This is a very steep climb for about 60 m, and there are many loose rocks. When you have attained enough elevation to be above the cliff, traverse to the west to the stream that supplies the waterfall. In the stream bed above the falls there are several xenoliths and schlieren of marble ± calcsilicate, surrounded by anorthosite. The largest of these bodies measures approximately 30 x 200 m in exposure, is compositionally zoned, and contains several unusual minerals. Most notably, the xenolith contains sanidinite facies index minerals wollastonite, monticellite (Mo_{92-89}), and akermanite as well as cuspodine, harkerite, and wilkeite (Kemp 1920; Baillieul 1976; Tracy *et al.* 1978; Valley and Essene 1980b). Other minerals present include garnet (Grs_{80-18}, And_{80-15}), spinel (Mg_{73}), calcite, forsterite (Fo_{92}), magnetite, clinopyroxene scapolite (Me_{78-50}), quartz, and titanite.

Field relations, deformation and geochronology make it clear that these marble bodies were entrained within the anorthositic magma before the peak of granulite facies metamorphism. The exact timing of intrusion vs. regional metamorphism is still a matter of debate. We strongly favor pre-metamorphic rather than deep syn-metamorphic intrusion as originally proposed by Valley and O'Neill (1982), but in either case it is certain that both anorthosite and marble experienced the pressures and temperatures of granulite facies metamorphism (Valley and Essene 1980b). Thus, the mineralogy of these bodies may be used to study the P-T fluid conditions of granulite facies metamorphism. The origin of these minerals, which we believe was at low P and high T, is irrelevant in this regard because of the pervasive nature of the granulite overprint.

Solid-solid mineral reactions at Cascade Slide indicate that P and T attained at least 7.4 kbar and 750 ˚C, respectively (Valley and Essene, 1980b; Bohlen *et al.*, 1985). Valley and Essene (1980b) describe assemblages of akermanite + monticellite + wollastonite with equilibrium metamorphic textures as well as symplectic intergrowths of wollastonite and monticellite. At these temperatures and pressures, the presence of wollastonite, monticellite or akermanite requires that log f_{CO_2} be ≤ 4.35, ≤ 3.32, or ≤ 2.5 respectively.

Further evidence that granulite facies fluid infiltration has not been important at Cascade Slide comes from oxygen isotopes (Valley and O'Neil, 1984; Valley 1985). Any fluids (H_2O or CO_2) passing through the xenolith would first have passed through the surrounding anorthosite ($\delta^{18}O = 9.7$). Subsequent exchange with the calcsilicates ($\delta^{18}O = 17.6$ to 26.1) would tend to homogenize this large premetamorphic difference with the result that $\delta^{18}O$ in the xenolith would be reduced. The highest values of $\delta^{18}O$ (26.1) in monticellite marble are thus very restrictive to theories of fluid infiltration and require fluid/rock < 0.1.

Three lines of evidence argue against the presence of fluid during the granulite facies metamorphism at Cascade Slide: 1) Assemblages of monticellite + forsterite + diopside + calcite + spinel plot in the fluid-absent field, including that if a fluid had existed, $P_{H_2O} + P_{CO_2} \leq 0.4$ kbar. 2) The large gradients in buffered values of f_{CO_2} across the body and the fragile nature of the buffering assemblages would have been erased by CO_2 infiltration. even by quantities as low as CO_2/rock = 0.001. 3) The preservation of high $\delta^{18}O$ in the core of the xenolith and the sharp gradients of up to 18 permil/15 m would all have been homogenized if either H_2O or CO_2 had infiltrated the xenolith in quantities greater that fluid/rock = 0.1. These results are all consistent with the polymetamorphic history proposed by Valley (1985).

Monticellite has also been found at Westin Mines (5 km to the E of Cascade Slide) where magnetite skarn replaces marble at the contact of the anorthosite massif (Valley and Graham, 1991). This locality is on private property and will not be visited. Magnetites from marble at this deposit were the first to be analyzed for oxygen isotope ratio by ion microprobe with accuracy of ±1‰ (1σ). This analysis yields spatial resolution as small as 2 μm and has reduced sample size by 11 orders of magnitude relative to conventional techniques, permitting new studies of oxygen diffusion, fluid exchange, and Adirondack cooling rate.

STOP A-5: WOOLEN MILL GABBRO

Description modified from Bohlen, McLelland, Valley, and Chiarenzelli (1992).

Park on the right side of the road opposite high roadcut on left. The cut shows metanorthosite intruded by a dark, fine-grained rock, first described by Kemp and Ruedemann (1910) as the "Woolen Mill Gabbro". It is a clinopyroxene-garnet-oligoclase granulite with considerable opaque oxides and apatite, and minor K feldspar and quartz. It contains a few large, uncrushed andesine xenocrysts, probably derived from the host anorthosite. The texture is that of a granulite, but the xenocrysts have apparently escaped recrystallization or grain-size reduction, even along their margins. This peculiar situation may be explained by static recrystallization of an initially fine-grained intrusive rock. The composition of rock is that of a somewhat K_2O rich (1.20 wt%) ferrogabbro of the type common in the Adirondack Highlands, especially near magnetite-ilmenite concentrations. It also is found associated with anorthosite at Split Rock Falls and near Elizabethtown, and is commonly present as disrupting material in block structure. Woolen Mill gabbro may represent gabbroic anorthosite magma enriched in mafic components by separation of cumulus plagioclase as suggested by mixing calculations (Ashwal 1978).
This is the type locality for deWaard's (1965) clinopyroxene-almandine subfacies of the granulite facies.

Cross the road and examine the outcrops in the stream bed. At the west end of the stream exposures, Woolen Mill gabbro clearly crosscuts anorthosite, and veins and dikes of the gabbro extend into the anorthosite. Within the anorthosite there is well-developed "block structure" where several types of anorthosite have undergone brittle fracture before being intruded by thin dikes or veins of mafic as well as felsic material. Some of these veins are identical to the mafic granulite in the roadcut (and at the west end of the stream exposure) and are part of the anorthosite suite. Some of the disrupting material is anorthositic gabbro more commonly associated with the anorthosite as on Giant Mountain or Lake Clear. In addition, a variable amount of granitic material is present in many of the veins as revealed by straining. The relationships here suggest formation of a plagioclase-rich cumulate, which was then fractured and intruded by a later mafic differentiate. This apparently brittle behavior supports a relatively shallow depth of intrusion. Notice also the very large (up to 10 cm) giant orthopyroxenes that occur in the anorthosite, especially near the contact with Woolen Mill gabbro.

The anorthosite in the stream bed contains the characteristic post-metamorphic alteration assemblages of calcite ± chlorite ± sericite that are commonly seen as late-stage, hairline vein fillings or as alteration products of Fe-Mg silicates throughout the Adirondacks (Buddington,1939; Morrison and Valley, 1988b). Average values of $\delta^{18}O$ and $\delta^{18}C$ for calcite are +12.6 and -2.2 permil, respectively, which suggests that the alteration fluids were deep seated in origin and exchanged with igneous as well as metasedimentary rocks. These veins are related to the formation of at least some high-density, CO_2-rich fluid inclusions and the temperatures of alteration are estimated at 300 ˚-500 ˚C (Morrison and Valley, 1988a,b).

The retrograde fluids that have infiltrated the anorthosite to precipitate calcite have not significantly altered its oxygen isotopic composition. Values of $\Delta_{\text{(calcite-plagioclase)}}$ range from 0.96 to 6.6, indicating that the isotopic composition of the alteration minerals was controlled primarily by the hydrothermal fluid and that the $\delta^{18}O$ of the host rock remained largely unchanged due to low fluid/rock ratios.

Values of $\delta^{18}O$ (plag) for the "blocks" and their host anorthosite at this outcrop range from +8.5 to +9.3. In general, the metanorthosites in the NE part of the massif are somewhat more isotopically heterogeneous than those in the northwestern part of the massif, but they show the same roughly 2.5 permil enrichment in $\delta^{18}O$ relative to "normal" anorthosites worldwide (Morrison and Valley, 1988a).

STOP B-1: GORE MOUNTAIN

Description modified from Kelly and Peterson (1993).

The Barton Mines Corporation open pit mine is located at an elevation of about 2600 feet on the north side of Gore Mountain. For 105 years, this was the site of the world's oldest continuously operating garnet mine and the country's second oldest continuous operating mine under one management. The community at the mine site is the highest self-sufficient community in New York State. It is 10 miles from North Creek and 5 miles from State Route 28 over a Company-built road that rises 300 feet per mile. This road, like others in the vicinity, is surfaced with coarse mine tailings. About eleven families can live on the property. The community has its own water, power, and fire protection systems. On the property are the original mine buildings and the Highwinds Inn, built by Mr. C.R. Barton in 1933 as a family residence. The Inn is now privately leased from the corporation and operates 10 months per year. It offers a four-bedroom lodge, a four star dining room, cross-country skiing and fantastic views of the Siamese Wilderness Area.

The garnet is used in coated abrasives, glass grinding, metal and glass polishing, and even to remove the red hulls from peanuts. Paint manufacturers add garnet to create non-skid surfaces and television makers use it to prepare the glass on color picture tubes. Barton sells between 10,000 and 12,000 tons of garnet abrasive annually. About 40% of the company's shipments are to foreign countries. All current U.S. production of technical grade garnet is limited to the Barton mines from where it is shipped world wide for use in coated abrasives and powder applications (Austin, 1993a, b).

Garnet has been designated as the official New York State gemstone. Barton produces no gem material but collectors are still able to find gem rough. Stones cut from Gore Mountain rough material generally fall into a one to five carat range. Garnets from this locality are a dark red color. Special cutting schemes have been devised for this material in order to allow sufficient light into the stone.

History

The first 80 years of the history of the Barton garnet mines has been compiled by Moran (1956) and is paraphrased below. Mr. Henry Hudson Barton came to Boston from England in 1846 and worked as an apprentice to a Boston jeweller. While working there in the 1850's, Barton learned of a large supply of garnet located in the Adirondack Mountains. Subsequently, he moved to Philadelphia and married the daughter of a sandpaper manufacturer. Combining his knowledge of gem minerals and abrasives, he concluded that garnet would produce better quality sandpaper than that currently available. He was able to locate the source of the Adirondack garnet stones displayed at the Boston jewelry store years before. Barton procured samples of this garnet which he pulverized and graded. He then produced his first garnet- coated abrasive by hand. The sandpaper was tested in several woodworking shops near Philadelphia. It proved to be a superior product and Barton soon sold all he could produce.

H.H. Barton began mining at Gore Mountain in 1878 and in 1887, bought the entire mountain from New York State. Early mining operations were entirely manual. The garnet was hand cobbed i.e. separated from the waste rock by small picking hammers and chisels. Due to the obstacles in moving the ore, the garnet was mined during the summer and stored on the mountain until winter. It was then taken by sleds down to the railroad siding at North Creek whence it was shipped to the Barton Sandpaper plant in Philadelphia for processing. The "modern" plant at Gore Mountain was constructed in 1924. Crushing, milling, and coarse grading was done at the mine site. In 1983, the Gore Mountain operation was closed down and mining was relocated to the Ruby Mountain site, approximately four miles northeast, where it continues at present.

Mining and Milling

The mine at Gore Mountain is approximately one mile in length in an ENE-WSW direction. The ore body varies from 50 to 400 feet and is roughly vertical. Mining was conducted in benches of 30 feet using standard drilling and blasting techniques. Oversized material was reduced with a two and one-half ton drop ball. The ore was processed through jaw and gyratory crushers to liberate the garnet and then concentrated in the mill on Gore Mountain. Garnet concentrate was further processed in a separate mill in North River at the base of the mountain. Separation of garnet is accomplished by a combination of concentrating methods including heavy media, magnetic, flotation, screening, tabling, and air and water separation. Processes are interconnected and continuous or semi-continuous until a concentrate of 98% minimum garnet for all grades is achieved (Hight, 1983). Finished product ranged from 1/4 inch to 1/4 micron in size.

Characteristics of Gore Mountain Garnet

The garnet mined at Gore Mountain is a very high quality abrasive. The garnets display a well developed tectonic parting that, in hand specimen, looks like a very good cleavage. This parting is present at the micron scale. Consequently, the garnets fracture with chisel-like edges yielding superior cutting qualities. The garnet crystals are commonly 12 inches in diameter and rarely up to thirty-six inches with an average diameter of 4 inches (Hight, 1983). The composition of the garnet is approximately 37-43% pyrope, 40-49% almandine, 13-16% grossular and 1% spessartine (Levin, 1950; Harben and Bates, 1990). Chemical zoning in garnet, where present, is very weak and variable (Luther, 1976). Typical chemical analyses of the garnet and associated tschermakitic hornblende (Leake, 1978), andesine and hypersthene are given in Table A-1. The garnet has a hardness between eight and nine and an average density of 3.95 gm/cm^{-3}.

Geology

The garnet mine is entirely hosted by a hornblende-rich garnet amphibolite unit sandwiched between a small olivine meta-gabbro body which contacts meta-anorthosite to the north and is in fault contact with meta-syenite to the south (Fig. A-1,A-2). Preserved in the olivine meta-gabbro are igneous textures and faint igneous layering, and a xenolith of anorthosite has been reported in the gabbro (Luther, 1976). Prior to metamorphism, the rock was composed of plagioclase, olivine, clinopyroxene, and ilmenite. During metamorphism, coronas of orthopyroxene, clinopyroxene, and garnet formed between the olivine and the plagioclase and coronas of biotite, hornblende and ilmenite formed between plagioclase and ilmenite (Whitney and McLelland, 1973, 1983). The contact between the olivine meta-gabbro and the garnet amphibolite is gradational through a transition zone 2-3 meters wide. Garnet size increases dramatically across the transition zone from <1 mm in the olivine meta-gabbro, to 3 mm in the transition zone to 50 to 350 mm in the amphibolite (Goldblum and Hill, 1992). Crossing the transition zone the increase in garnet size is paralleled by a ten-fold increase in the size of hornblende and biotite, olivine disappears, modal clinopyroxene decreases as it is replaced by hornblende and spinel-included plagioclase grades to inclusion-free plagioclase. The modal percent garnet varies from 5 to 20 percent but averages 13 percent in both the olivine meta-gabbro and the amphibolite (Luther, 1976; Hight, 1983; Goldblum, 1988). At the west end of the mine, a garnet hornblendite with little or no feldspar is locally present. This rock probably represents original ultramafic layers in the gabbro (Whitney *et al.*, 1989). In the more mafic portions of the ore body, the garnets are rimmed by hornblende up to several inches thick. Elsewhere, the ore is less mafic, and the rims contain plagioclase and orthopyroxene. The amphibolite is thought to represent a retrograded zone of granulite facies rocks (approximately 750 C and 7.5 kilobars).

A strong, consistent lineation and a weak planar fabric coincides with the zone of large garnets and is an important characteristic of the ore zone (Goldblum and Hill, 1992). The lineation is defined by parallel alignment of prismatic hornblende grains, elongate segregations of felsic and mafic minerals, plagioclase pressure shadows and occasional elongate garnet. The foliation is defined by a slight flattening of the felsic and mafic aggregates.

Table A-2. Whole-rock Chemical Analyses

Oxide	Olivine Meta-gabbro	Garnet Ore
SiO_2	47.14	45.68
TiO_2	0.81	0.78
Al_2O_3	16.98	17.32
Fe_2O_3	0.69	1.30
FeO	11.13	9.67
MnO	0.16	0.15
MgO	11.04	10.97
CaO	8.05	8.58
Na_2O	2.54	2.85
K_2O	0.56	0.59
P_2O_5	0.10	0.10
H_2O	0.44	1.16
Total	99.64	99.15

Chemical analyses of the olivine meta-gabbro and garnet amphibolite show that the garnet ore was derived by retrograde isochemical metamorphism, except for an increase in H_2O and fO_2, of the olivine meta-gabbro (Table A-2; Luther, 1976).

Origin of Garnet

The formation of the garnets is not completely understood. Whereas the Gore Mountain deposit is the largest known, it is not unique in the Adirondacks. Elsewhere, there are occurrences of garnet amphibolite that are texturally and mineralogically similar. These are usually located on the margins of gabbroic rock bodies. Although the garnets at Gore Mountain are atypical in size, the modal amount of garnet is not unusually high for Adirondack garnet amphibolites. The ore at the currently operating Barton Corporation mine at Ruby Mountain, for example, is of the same tenor but the garnets rarely are larger than one or two inches. Petrologic studies (Buddington, 1939, 1952; Bartholomé, 1956, 1960; Luther, 1976; Sharga, 1986; Goldblum, 1988; Goldblum and Hill, 1992) have agreed that the growth of the large garnets is related to a localized influx of water at the margin of a competent meta-gabbro body during amphibolite facies metamorphism. Southward across the transition zone increased ductile deformation resulted in grain size reduction of plagioclase and clinopyroxene. The presence of deformation lamellae, undulose extinction, deformation twins, bent twins, and subgrain boundaries in plagioclase are evidence for plastic deformation and high strain, and abundant hornblende is a testament to the large amount of fluid that has permeated the rocks. Recognition that the orebody, retrograde metamorphism and L-S deformation fabric all coincide with the southern margin of the olivine meta-gabbro led Goldblum and Hill (1992) to hypothesize that the high fluid flow required for growth of large garnets was the result of high-temperature shear zone that crossed the contact of lithologies with contrasting rheologies and propose that ductility contrasts at this lithologic contact was responsible for localizing garnet growth, retrograde metamorphism and fabric development. Grain size reduction by cataclasis was replaced by recrystallization as the hydrated ore body replaced the olivine meta-gabbro during ductile deformation.

The Gore Mountain garnets are chemically homogeneous indicating that (a) the garnets grew under conditions in which all chemical components were continuously available and (b) that temperature and pressure conditions must have been uniform during the period of garnet formation. If the garnet amphibolite zone within the the original gabbro represents a zone wherein fH_2O was higher than elsewhere during the granulite facies metamorphism, this may have facilitated diffusion and favored growth of very large garnets and thick hornblende rims at the expense of plagioclase and pyroxene. The presence of volatile components, particularly H_2O, promotes the growth of large crystals. The physical and chemical conditions necessary for the nucleation of a mineral may be different from the conditions necessary for the growth of that mineral. It has been speculated (Luther, 1976) that the physico-chemical environment was poor for the nucleation of garnet but that the environment was conducive to the growth of garnet.

Therefore, the garnet crystals that did nucleate grew to large size. Growth might have been abetted by aqueous transport of components due to elevated fH_2O in this portion of the ore body.

Table A-1. Microprobe Analyses of Gore Mt. Garnet, Hornblende, Orthopyroxene and Feldspar

	GARNET #29	GARNET #41	HBL #30	HBL #31	OPX #37	PLAG #33	PLAG #34
Oxide Weight Percent							
SiO_2	39.43	39.58	44.13	44.26	25.41	27.16	27.29
Al_2O_3	21.40	21.20	12.36	12.53	1.22	13.56	13.67
TiO_2	0.05	0.10	1.28	1.45	0.04	0.00	0.00
FeO^*	22.80	24.45	3.49	3.03	14.82	0.05	0.05
$Fe_20_3^*$	1.44	0.72	8.12	8.93		0.00	0.00
MgO	10.65	9.60	14.51	14.50	14.87	0.00	0.00
MnO	0.48	0.74	0.06	0.08	0.11	0.00	0.00
CaO	3.85	3.97	10.56	18.48	0.32	6.38	6.47
Na_2O	0.00	0.00	2.48	2.43	0.02	4.65	4.70
K_2O	0.00	0.00	0.57	0.55	0.00	0.17	0.18
Cl	0.00	0.00	0.02	0.00	0.00	0.00	0.00
F	0.00	0.00	0.03	0.00	0.00	0.00	0.00
H_2O (OH)*			2.06	2.10			
O = Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O = F	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.09	100.36	99.66	100.33	101.08	99.20	99.87
Atoms							
Si	2.997	3.020	6.348	6.320	0.984	2.633	2.627
Al^{iv}			1.652	1.680	0.016	1.368	1.370
Al^{vi}	1.918	1.907	0.444	0.429	0.013		
Ti	0.003	0.006	0.139	0.156	0.002	0.000	0.000
Fe^{2+}	1.449	1.561	0.420	0.362	0.289	0.002	0.003
Fe^{3+}	0.082	0.041	0.878	0.959	0.000	0.000	0.000
Mg	1.206	1.092	3.111	3.085	0.666	0.000	0.000
Mn	0.031	0.048	0.008	0.009	0.002	0.000	0.000
Ca	0.313	0.325	1.628	1.604	0.009	0.433	0.436
Na	0.000	0.000	0.692	0.672	0.001	0.551	0.553
K	0.000	0.000	0.104	0.101	0.000	0.012	0.012
Cl	0.000	0.000	0.005	0.000	0.000	0.000	0.000
F	0.000	0.000	0.014	0.000	0.000	0.000	0.000
O	12.000	12.000	22.000	22.000	3.009	8.036	8.029
OH			1.981	2.000			
	And 4.1	And 2.1	NaB 0.372	NaB 0.396	En 69.1	A 0.996	A 1.001
	Alm 48.3	Alm 52.0	NaA 0.320	NaA 0.275	Fs 30.0	T 4.002	T 3.997
	Pyp 40.2	Pyp 36.4	KA 0.104	KA 0.101	Di 0.6	Ab 55.3	Ab 55.2
	Sps 1.0	Sps 1.6			Hd 0.3	An 43.5	An 43.6
	Grs 6.3	Grs 7.9				Or 1.2	Or 1.2

OPX (hypersthene) normalized to 2 cations EUP-93

PLAG (andesine) normalized to 5 cations

HBL (tschermakitic hornblende) normalized to 13 M1+M2+M3+T cations

GARNET (almandine-pyrope) normalized to 8 cations and 12 anions

* Calculated by charge balance

STOP B-2: THE GLEN

Description modified from Isachsen (1965)

The calcite marble and calc-silicate beds here are highly-deformed, having been isoclinally folded and refolded. The relatively competent amphibolite layers have been stretched, attenuated, and dismembered well beyond the boudinage stage so that they occur as disconnected lenses, hooks, and clots. Such floating fragments have sometimes been picturesquely tagged "tectonic "fish." Minerals that can be readily found and identified in the marble include calcite, graphite, diopside, forsterite, and titanite. Calc-silicate reaction zones can be observed between the marble and many of the mafic units. Local pockets of very course calcite occur with obvious twin lamellae.

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