USING ERRATIC BOULDERS TO MAP THE BASEMENT IN LONG ISLAND SOUND

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ABSTRACT

We have evaluated the provenance of several hundred erratic boulders on the Stony Brook University campus. The campus is on the Harbor Hill Moraine which formed during the last glacial maximum. We assume that the population of boulders which is most numerous and least rounded is derived from the nearest basement to the north along the path of the glaciers. Hand specimen evaluation, petrographic microscope studies and Ar-Ar ages on mica are consistent with most of the granitic boulders being derived from a nearby leucocratic Avalon basement source. There is only a small population of rocks representing the Iapetus Terrane, the nearest presently exposed basement immediately across Long Island Sound. The Avalon Terrane with leucocratic granitic rocks in Connecticut is too far to the east to be a major source of boulders. There is also a fair proportion of basalt boulders on campus similar to those in the Hartford Basin in Connecticut. However, the Hartford Basin is also too far to the east to be a major source of basalt boulders. During the last glacial maximum much of the bottom of Long Island Sound basin was exposed basement rock. There is geophysical evidence that the Hartford Basin extends into Long Island Sound and is directly north of Stony Brook. Our conclusion is that most of the boulders on campus are derived from the basement of Long Island Sound immediately to the north and that this basement consists of Avalon Terrane cut by a Triassic rift basin.

INTRODUCTION

Hundreds of boulders from 25 to 300 cm in diameter are scattered about the campus of Stony Brook University. They were excavated from the underlying glacial sediments on campus during construction of roads, buildings, *etc*. The Stony Brook campus is on the Stony Brook Moraine which was formed near the end of the Wisconsinan some 20,000 years ago (Sirkin, 1986). Based on observations at construction sites and from a few bore holes, the glacial sediments consist of an upper layer of loess usually less than one meter thick which overlies a layer of till about one meter thick. Below the till are sands, gravels, and varved fine sand and clay that have been glaciotectonically disturbed. While the overlying till where exposed has a relatively high concentration of boulders, it is not clear that all of the boulders were derived from this till.

In any case, glacier(s) brought the boulders to the campus. The dominant direction of travel of the glacier(s) was from the north across what is now Long Island Sound. The nearest presently exposed outcrops are in southern Connecticut some 15 to 20 miles to the north. However, when the last Wisconsinan glacier advanced toward present day Long Island the bottom of much of the northern part of the Long Island Sound Basin was exposed basement rock (Fig. 1). The sources of the boulders on campus could be anywhere to the north along the paths of the glaciers. If we can estimate the distance that the boulders have traveled, we may even be able to evaluate the types of basement rocks underlying Long Island Sound.

The assumptions used for this study are that the most numerous and least rounded boulders are derived from the nearest basement. The least numerous and most rounded boulders are from basement at greater distances. Three hundred seventy three boulders, from a 0.3 square mile area of the SUNY Stony Brook campus, have been classified according to size, shape, roundness, breakage, sphericity, combined mean size and rock type (Pacholik, 1999). These results have been used to estimate possible distances to the basement sources of the boulders.

The boulders were derived by plucking or quarrying at the base of the glacier. Once plucked these boulders stay at the base of the glacier unless there is an obstruction along the path of the glacier in which case the boulder may be thrust above the glacier base. This was a temperate glacier with a wet bottom so that most of the forward motion (transport) of the glacier was associated with basal sliding and shearing of the sediment (till) at the base of the glacier. The basal transport zone (shear zone) within the till is usually only a few cm to tens of cm thick and rises or lowers within the till layer with changes in the amount of melting or regelation (freezing) (Boulton, 1978). Because of these changes in the position of the basal transport zone, particles in the till will at various times be in or below the basal transport zone. In a temperate glacier with a wet base, there is continuous melting at the base of the glacier. As a result, sedimentary particles tend to stay at the base. However, at the front of temperate glaciers in the marginal zone of compression where there may be permafrost or freezing during the winter the base of the glacier may be frozen to the substrate and basal sediments may travel up into the glacier along englacial thrust faults (Boulton, 1978; Benn and Evans, 1998, p. 538).

Continental glaciers such as the last Wisconsinan glacier that visited Long Island were thick enough that all of the terrane to the north of Long Island was below the surface of the glacier. Thus, essentially all of the boulders were derived by plucking or quarrying at the base of the glacier. Largely the rock type and the nature of the joints or weakness within the basement rock determine the original shape of boulders entrained in the base of a glacier. If the joints are equally spaced, the boulders will be block shaped, that is approximating cubes. If the joints are not equally spaced, the boulders can be slabs, that is, they are elongated in two dimensions, or blade or rod shaped elongated in one dimension. Generally, the initial edges of the boulders were angular and sharp unless the rock was extensively weathered. Due to the friction between the boulders and the other particles in the traction zone, the boulders travel slower than the overlying glacier (Boulton, 1974). Once the boulder enters the basal transport zone, it crushes and striates the underlying bedrock and is worn down by contact with the bed and the other particles being transported. If the boulders are block shape, they are rolled and abraded on all surfaces. (Granites and granite gneisses tend to form block-shaped boulders.) If the boulders are slab or blade shaped, they tend to slide rather than roll and are preferentially abraded on one surface. Slab or blade shaped boulders will on occasion be lifted by the basal ice, rotated and abraded on other surfaces. However, boulders that do not roll easily will tend

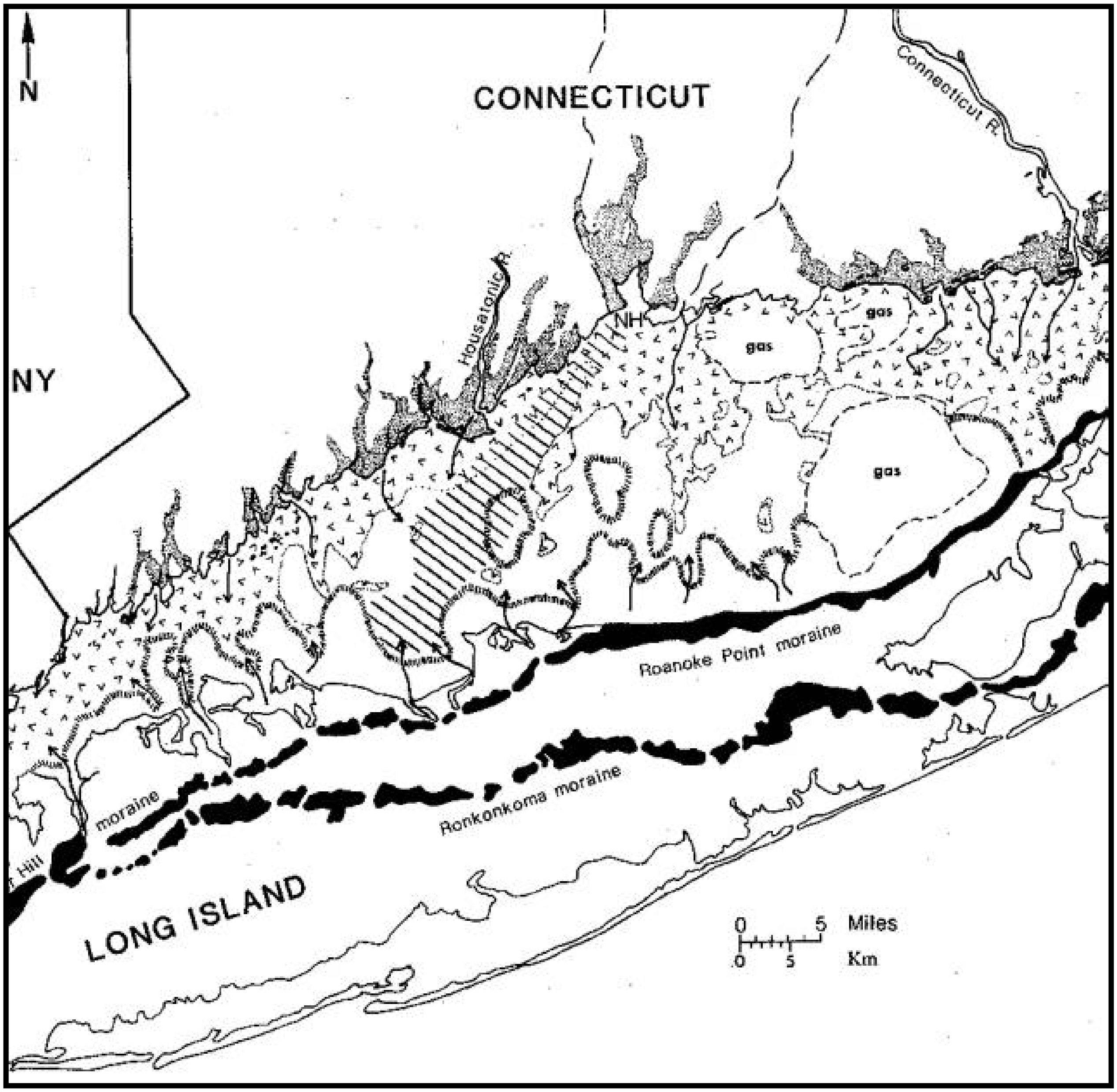

Fig. 1. Map showing rocks exposed at the bottom of Long Island Sound basin at the last glacial maximum. The checkmarked area is basement. The hatched area in Long Island Sound is an area of deep basement rocks that may represent the location of the extension of the Hartford Basin into Long Island Sound. The bold dashed lines extending to the north from Stony Brook University are the estimated range of paths of the last glacier. Map is modified from Lewis and Stone (1991).

to form "glacial flat iron" boulders (Boulton, 1978). Boulders larger than about 0.5 to 1 meter generally become embedded in the till and its movement is retarded. As a result it develops a shape similar to that of a *roche moutonee* (Boulton, 1978).

The boulders in the basal transport zone are subject to abrasion and crushing. The result of the abrasion by sand and silt in the basal transport zone is to round off the sharp edges and polish the surface. However, the boulders are continually broken by collision with the basement or other boulders in the basal transport zone. As a result, fractured surfaces with sharp edges develop on the boulders, which then begin to be rounded. Therefore, the mature shape of initially blocky boulders in the basal transport zone is well rounded with a fractured surface with partially rounded edges.

There are numerous examples of boulders (erratics) traveling many hundreds of kilometers. However, this is not the norm for all boulders. For example, Salonen (1986, 1987) found that after 5 kilometers of travel from their source, till contained only one-half of the proportion of the initial particles. Humlum (1985) found for cobbles derived from a rhyolite plug, that their size, shape and roundness reached an equilibrium state after transport of only 500 meters. This is in part because the larger clasts became lodged in the till while the smaller clasts continued to stay in basal transport. Goldthwait (1968) found that less than 0.1% of any rock type is found beyond 21 miles of it source. Due to the large number of advances and retreats of glaciers during the Pleistocene, boulders may have a complicated history of being removed from the bedrock, transported, deposited and then reincorporated in the basal transport zones of later glaciers allowing much longer distances and dispersed paths of transport.

Thus, the angularity gradually decreases during sub-glacial transportation. As a result, the roundness of a population of boulders should be directly related to the distance of transport. While Krumbein (1941) suggested that the roundness be halved for broken pebbles, we suggest that in order to evaluate the distance traveled by a suite of boulders, one should base the roundness on the unbroken surfaces. The roundness of a broken surface is related to the distance from where breakage occurred.

POTENTIAL BEDROCK SOURCES OF BOULDERS

The general information about bedrock of the Long Island Sound basin is derived from geophysical studies; but specific data about types of basement rocks are not known. The crystalline bedrock surface of Connecticut generally dips southeastward from the Hartford Basin (Pierce and Taylor, 1975). The bedrock structure of Connecticut extends offshore, according to the magnetic map of Long Island Sound by Grim *et al*. (1970). The map of Lewis and Stone (1991) based on high -resolution seismic profiles shows the pre-glacial geology of Long Island Sound that includes crystalline basement, an area of anomalously deep bedrock (interpreted to be an extension of the Hartford basin) and the Cretaceous sediments. In most places the exposed crystalline basement extended well into the Long Island Sound. As a result the last glacier may have transported boulders derived from the basement now underlying the Long Island Sound to the SUNY Stony Brook campus. This basement is otherwise inaccessible for sampling.

Sanders (1960, 1963) proposed that Triassic-Jurassic rocks similar to those found in the Hartford Basin extended into Long Island Sound. A driller reported encountering several hundred feet of sandstone near Northport, Long Island (De Laguna and Brashears, 1948). A magnetic map of Long Island Sound shows a change in character of the magnetic anomalies where the basin is proposed to be (Grim *et al*. 1970). In the New Haven area, Rodgers (1985) showed an extension of the eastern border fault of the Hartford Basin into Long Island Sound. The possible extension of the Hartford Basin is shown in the seismic study of Lewis and Stone (1991) and Lewis and DiaGiacoma-Cohen (2000) as a deep bedrock anomaly (Fig. 1). If the boulders are derived from a northerly direction there should be few or no boulders of Hartford Basin sedimentary rocks or basalts found on campus, because the Hartford Basin is to the east of the area. If there is a rift basin in the Long Island Sound north of Stony Brook we should expect to find a relatively large number of basaltic boulders on campus. The likelihood of numerous large sedimentary boulders is small because of the size of the beds, the close spacing of the joints and the friable nature of the sedimentary rocks in these basins.

The crystalline bedrock surface in Long Island Sound is closest to the surface along the eastern side of the Eastern Border fault taking into consideration that surfaces of bedrock generally dip southeastward from the Connecticut coast (Grim *et al*., 1970). West of New Haven, Paleozoic schist gneiss and granites of Iapetos terrane (Rodgers, 1985) are exposed along the north shore of Long Island Sound. The Bedrock surface under western L.I. dips southeastward (Newmen, 1977).

Hand specimen descriptions of the boulders studied and petrographic descriptions of twenty-four thin sections for the most common boulders have been used to compare the boulders on campus to possible source rocks in southern Connecticut typical of those which may underlie Long Island Sound. Ar-Ar ages of mica and hornblende were also determined to verify these observations.

The terranes exposed in southern Connecticut (Rodgers, 1985) going from west to east include (see Fig. 2):

Grenville gneisses about 1.1 Ga in age which formed the basement to Laurentia (proto-North America)
Overlying Cambro-Ordovician metasedimentary rocks which were deformed and metamorphosed during the Taconian Orogeny (440 to 455 Ma),
Schists and gneisses of the Iapetus terranes which were metamorphosed during the Acadian Orogeny (360 t0 420 Ma) include:
  Schists and gneisses of the Connecticut Valley Synclinorium
  Schists and gneisses of the Bronson Hill anticlinorium
  Schists and gneisses of the Merrimack synclinorium,
Schists and gneisses of the Avalonian terrane were metamorphosed during the Alleghenian Orogeny. The older gneisses are 600 to 700 Ma, the younger gneisses and plutons are about 300 Ma.
Triassic and Jurassic clastic sediments, basalt and diabase of the Hartford Basin, a rift basin,
Holocene to Cretaceous mainly unconsolidated sediments make up the Coastal Plain that dips gently to the southeast.

The Avalonian terrane extends south of the Bronson Hill Anticlinorium. This boundary if it extends westward would suggest that the basement rocks underlying the Long Island Sound may be part of the Avalonian terrane.

Three hundred and seventy three boulders size, shape, roundness, breakage, sphericity, combined mean size and rock type

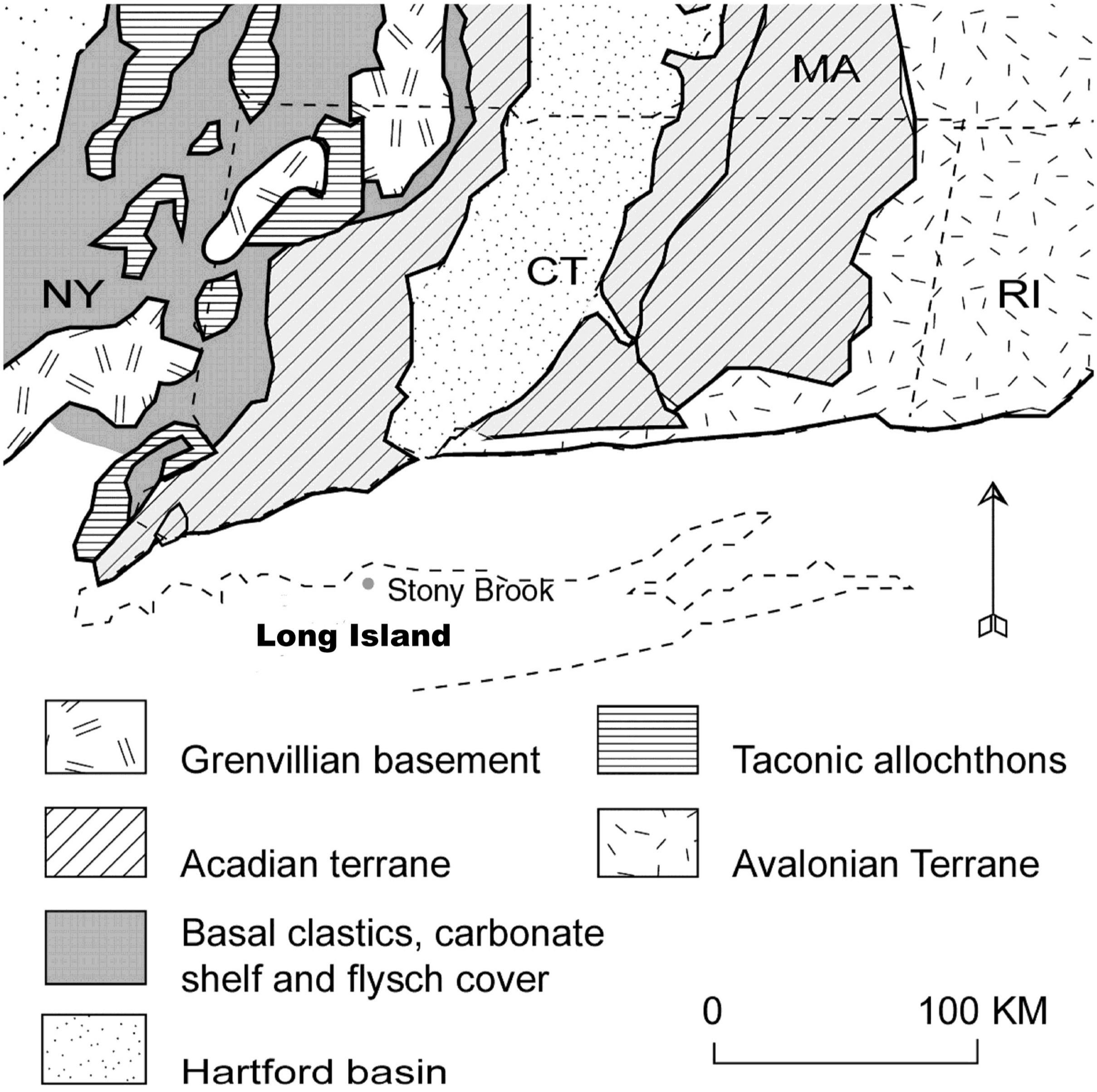

Fig. 2 Map of terranes in southern New England and eastern New York (Zhong, 2002)

(Pacholik, 1999 & 2000, and Pacholik and Hanson, 2001). The results of the comparison of rock types based on the macroscopic and microscopic studies show that 86% of the boulders are similar to rock types in the Avalonian Terrane, 8% are basalts, 3% are similar to rock types in the Iapetus terranes, 3% are quartz vein, the rest are individual rock types.

DISTINGUISHING CHARACTERISTICS OF BASEMENT ROCK TYPES

Granites, gneisses and deformed pegmatites are the dominant rock types which are easily distinguishable from the basalt and quartz-vein or quartzite boulders. The types of pegmatite in boulders are distinguished by the rock types included with the intrusive (?) pegmatite in the boulders. The following descriptions are based on our observations and those in the literature. In general the granites and gneisses of the Avalonian Terrane are more leucocratic than those of the Connecticut Valley Synclinorium.

Granites and Gneisses of the Avalonian Terrane

The Branford type massive and foliated quartz monzonite is creamy-white to very light gray, mostly medium, particularly in the vicinity of pegmatite, coarse – grained, of hypidiomorphic granular fabric. The light cream color potash feldspar, white plagioclase, and quartz content give the rock a leucocratic creamy-white appearance. Biotite and muscovite are present only in a small percent of the rock's body mass. Muscovite is not visible in all samples. Small to medium grains of garnet are very common and give the rock a speckled appearance. Potash feldspar is coarser in the vicinity of pegmatite. In the foliated version, the quartz is anhedral and interstitial forming lenses around feldspathic aggregates (Mikami and Digman, 1957).

The Stony Creek type pink granite is medium to medium coarse-grained. The pink color is a result of the dominance of pink potash feldspar over white plagioclase and clear quartz. The fine grained biotite grains often define a weak foliation. Biotite and muscovite are of minor abundance. Garnet is rare.

The Stony Creek gneiss is medium-grained, gray, and strongly foliated. The potash feldspar commonly forms lenticular, augen, and is surrounded by lenticular quartz. The fine-grained biotite is very minor in abundance and not easily seen in hand specimen (Mikami and Digman, 1957).

A few of the Stony Brook boulders belong to gneisses of the Middletown formation (Mikami and Digman, 1957). This light gray medium, even grained, foliated, hornblende, biotite granite gneiss differs from the other Avalonian rock types by its color texture and presence of hornblende. Biotite defines the foliation in this gneiss. Some samples contain elongated lenses of quartz. Red to purple garnet is rare.

Granites and Gneisses of the Connecticut Valley Terrane

While we expected to find boulders of some of these rocks exposed to the north in Connecticut, we only found boulders of the Harrison Gneiss.

Shelton Granite is a gray, medium- to fine-grained, poorly to well foliated gneiss has with muscovite defining the foliation. Muscovite has an abundance of 10 to 15 percent muscovite; biotite is less than 1 percent. The fine-grains of feldspar are creamy-yellow or beige. The weathered surface has rusty spots around small grains of garnet (Crowley, 1968).

Ansonia gneiss is fine-grained; the higher percentage of biotite (around 3 percent) gives the rock a dark gray appearance. The more abundant, coarser muscovite (5 to 9 per cent) defines the foliation (Crowley, 1968).

Collinsville granitic type variations have a dominant content of feldspar in its proportion to quartz (mostly more than twice more than feldspar), and a high concentration of biotite (around 10 percent of the rock mass). The decrease of the grain size of the felsic components is associated with the increase of the biotite content. The feldspar is light gray which gives the rock a cool appearance in comparison with the pink Stony Creek type granite (Crowley, 1968).

The Saugatuck gray to pink granitic gneiss is fine to medium grained even textured with a significantly higher concentration of biotite than the Stony Creek granite with which it might be confused.

The Pinewood Adamellite, a fine to medium grained, light gray muscovite granite has an evenly- grained texture and does not contain biotite, which distinguishes it from the Stony Creek granite (Crowley, 1968).

The Harrison Gneiss (Rodgers, 1985) includes a group of dark to light gray gneisses easily distinguished from the other more leucocratic rock types in the Connecticut Valley Terrane and the Avalonian Terrane. These gneisses generally contain biotite and hornblende and include augen gneiss. The Beardsley gneiss is a medium-grained, strongly lineated, weakly foliated, biotite, hornblende, quartz, feldspar gneiss. The Pumpkin Ground gneiss is a medium-grained, moderately foliated, gray, biotite, quartz, feldspar augen gneiss. The augen, are megacrysts of potash feldspar up to 3 cm in length

AR-AR AGES

Muscovite, biotite and hornblende grains were co-irradiated with hornblende monitor standard Mmhb (age = 525 Ma, Samson and Alexander, 1987) in the Cd-lined, in core facility (CLICIT) at the Oregon State reactor. Analyses were made in the Ar geochronology laboratory at Lamont-Doherty Earth Observatory. Individual grains were fused with a CO_2 laser, and ages were calculated from Ar isotope ratios corrected for mass discrimination, interfering nuclear reactions, procedural blanks and atmospheric Ar contamination. The analytical uncertainty for the single grain micas for all but one of the samples is 1.5 million years or less. One biotite sample has an analytical uncertainty of 6 Ma. The data for the Ar-Ar ages are in Table 2.

Fig. 3 is a map showing the glacial lobes that advanced on Long Island during the last glacial maximum and contours of Ar ages for mica in the basement rocks in eastern New York and Connecticut. Rocks associated with or affected by the Taconian Orogeny are found in the western Hudson Highlands and the Taconic Mountains of eastern New York and western New England. The Taconian Orogeny began about 455 million years ago but much of the area affected by the Taconian Orogeny was later affected by the Acadian Orogeny as a result biotite and muscovite K-Ar ages for the Taconian terrane rocks were reset to between 400 to 350 Ma

(Long, 1962). The rocks affected by the Acadian orogeny in western Connecticut have biotite and muscovite ages between 350 to 320 Ma (Scott *et al*., 1980, Seidemann, 1980). The mica ages of Iapetus terrane rocks in the southern part of western Connecticut were reset by Alleghenian events (Clark and Kulp, 1968, Cosca *et al*, 1997). In Connecticut the rocks affected by the Alleghanian Orogeny have mica ages between 220 to 300 Ma (Zartman *et al*, 1970, Scott *et al*., 1980, Dallmeyer, 1982 Cosca *et al*, 1997), with older ages in the west and younger in the east.

Avalonian Boulders

Thirteen biotite and muscovite grains from four Branford type boulders (no. 4, 30, 31 and 44 Pacholik, 1999) give an average age of 237 Ma with a standard deviation of 11 Ma. Ten muscovite and biotite grains from three Stony Creek type boulders (no. 19, 22, and 27, Pacholik, 1999) give an average age of 234 Ma with a standard deviation of 5 Ma. These ages are consistent with these boulders being derived from an Avalonian terrane.

Six biotite grains from two Middletown type boulders give an average Ar-Ar age of 234 Ma with a standard deviation of 5Ma. Three biotite grains from one boulder (no. 27a, Pacholik, 1999) give an average age of 280 Ma with a range of 279-283 Ma. These ages are also consistent with these boulders being derived from an Avalonian terrane. It is not clear why biotite from boulder 27a gives a significantly older age.

Iapetus Terrane Boulders in Connecticut Valley Synclinorium

Four biotite grains from one Beardsley type boulder (no. 37, Pacholik, 1999) give an average age of 284 Ma with a range of 280 to 291 Ma. Five biotite grains from a Pumpkin Ground type boulder (no. 20, Pacholik, 1999) give an average Ar-Ar age of 268 Ma with a range of 263 to 274 Ma. These mica ages are young compared to the more typical 320 to 350 m.y. ages for the Acadian micas. They are consistent with the finding of Clark and Kulp, 1968, and Cosca *et al*, 1997 that some mica ages for basement rocks in southern Connecticut have been reset by the Alleghenian Orogeny.

Other Boulders

Two biotite grains from a diorite boulder (no. 24, Pacholik, 1999) give Ar-Ar ages of 417 and 423 ma. These ages are too old to have been affected by Acadian events and are more typical of rocks affected by the Taconian Orogeny in western New England and eastern New York (Long, 1962). Thus, this boulder has traveled a long distance from the northwest.

Three chloritized biotite grains from a granodiorite boulder (no. 25, Pacholik, 1991) give an average age of 386 Ma with a range of 364 to 399 Ma. This rock shares a mineral composition with the Beardsley Gneiss, a member of the Harrison gneiss which was intruded during the Taconian Orogeny at 430 to 455 Ma (Sevigny and Hanson, 1995). These ages are older than most of the Acadian mica ages. Also, the range in ages suggests that the micas are Taconian and were partially reset by the Acadian orogeny. Again, this boulder has traveled a long distance from the northwest.

One hornblende grain from a hornblendite boulder (HOR, Pacholik, 1999) gives an Ar-Ar age of 369 Ma. This is an Acadian age and suggests that this boulder was probably derived from Connecticut essentially directly north of the campus.

One biotite grain from a biotite hornblende granite boulder (no.29, Pacholik, 1999) gives an age of 187 ± 6 Ma. This age is young even for a rock affected by the Alleghenian orogeny and most probably has undergone alteration or weathering.

The single grain Ar-Ar ages for mica and hornblende support the hypothesis that the boulders on the Stony Brook Campus were derived from the basement in Long Island Sound and that the basement is dominated by Avalonian terrane granites and gneisses. A small proportion of boulders typical of the Harrison Gneiss in Connecticut have Alleghenian metamorphic ages suggesting that they either they are from southern Connecticut or from Iapetus terrane underlying Long Island Sound. Diorite and granodiorite boulders have mica ages that are more typical of the Taconian terrane. This suggests that these boulders were derived from near the New York – New England border area to the northwest and traveled a significant distance, many tens of miles, to reach Stony Brook. One hornblendite boulder has a typical Iapetus terrane age and was probably derived from basement rock directly to the north in Connecticut. Thus, while most of the boulders most likely have the basement underlying Long Island Sound as their source, a small proportion of the boulders have traveled much further.

ROUNDNESS

Table 1 gives the percentage of boulders with each class of roundness for the boulder types found on the Stony Brook campus. Fig. 4 contains plots of rock type and roundness. Each of the Avalonian Terrane types of rocks has a bimodal distribution, except for the Branford-type pegmatite which has only one mode (Table 1). Also the total population of Avalonian types of rocks has a bimodal population. In the following discussion it is assumed that the mode is related to the average distance a class of boulders has traveled. The width of the peak should be an indication of the aerial extent of the rock type. The relative proportion of each rock type is also related to the aerial extent of the outcrop; however, the joint spacing in the different rock types may also be important. Widely spaced joints in a rock type will produce a larger proportion of boulders than the rock type with more closely space joints can produce. For example, the Stony Creek type granite is noted for its widely spaced joints and is a good quarrying stone.

Fig. 1 shows the possible field between the thick dashed lines for the paths of the glacier lobes that formed the Stony Brook Moraine. We would suggest that the bimodal distribution of the Avalonian Terrane type boulders suggests that they were derived from either side of the proposed extension of the Hartford Basin. Basalt boulders on campus have only one mode with a roundness that is intermediate to the two modes for the Avalonian Terrane type boulders. There are only a small number of Harrison Gneiss type boulders (13) with a generally a relatively low roundness suggesting that their source is either very close to the North Shore of Long Island or if they have a more distant source that they were carried englacially in the ice away from the basal zone where they would have been destroyed.

Table 2 Ar-Ar ages for single grains of mica and hornblende from boulders on the Stony Brook campus. Micas with the same boulder number are from the same boulder.

bio = biotite, musc = muscovite, chl = chlorite, hbld = hornblende

Rock Type	**Boulder (Mineral)**	**Age Ma**
Branford	4 (bio)	232.4 ± 0.7
Branford	4 (bio)	235.4 ± 0.5
Branford	4 (musc)	237.1 ± 0.8
Branford	4 (bio)	269.3 ± 0.7
Branford	30 (musc)	232.6 ± 2.8
Branford	30 (musc)	235.7 ± 0.5
Branford	30 (musc)	238.3 ± 0.6
Branford	31 (bio)	232.6 ± 0.8
Branford	31 (bio)	234.1 ± 0.9
Branford	31 (bio)	235.3 ± 0.7
Branford	44 (bio)	224.7 ± 0.5
Branford	44 (bio)	233.6 ± 0.5
Branford	44 (bio)	243.3 ± 0.6
Stony Creek	19 (bio)	228.0 ± 0.5
Stony Creek	19 (bio)	237.5 ±0.5
Stony Creek	22 (bio)	228.9 ± 0.9
Stony Creek	22 (bio)	229.8 ± 0.6
Stony Creek	22 (musc)	234.5 ± 0.7
Stony Creek	22 (musc)	235.4 ± 0.7
Stony Creek	22 (musc)	238.7 ± 0.8
Stony Creek	27 (bio)	232.0 ± 0.5
Stony Creek	27 (bio)	232.9 ± 1.3
Stony Creek	27 (bio)	245.3 ± 1.1

Rock Type	**Boulder (Mineral)**	**Age Ma**
Middletown	28 (bio)	230.1 ± 0.6
Middletown	28 (bio)	230.9 ± 0.5
Middletown	28 (bio)	232.7 ± 0.4
Middletown	32 (bio)	232.8 ± 0.9
Middletown	32 (bio)	233.0 ± 1.5
Middletown	32 (bio)	244.3 ± 1.5
Middletown	27a (bio)	279.1 ± 0.6
Middletown	27a (bio)	279.4 ± 0.6
Middletown	27a (bio)	283.4 ± 1.0
Beardsley	37 (bio)	280.2 ± 0.6
Beardsley	37 (bio)	280.5 ± 1.0
Beardsley	37 (bio)	284.6 ± 1.1
Beardsley	37 (bio)	290.5 ± 0.6
Pumpkin Ground	20 (bio)	264.7 ± 0.9
Pumpkin Ground	20 (bio)	266.7 ± 0.6
Pumpkin Ground	20 (bio)	269.1 ± 0.8
Pumpkin Ground	20 (bio)	270.2 ± 0.5
Pumpkin Ground	20 (bio)	273.5 ± 0.5
Diorite	24 (bio)	417.2 ± 2.1
Diorite	24 (bio)	423.2 ± 1.2
Granodiorite	25 (bio-chl)	364.1 ± 0.7
Granodiorite	25 (bio-chl)	395.7 ± 0.9
Granodiorite	25 (bio-chl)	399.6 ± 0.8
Hornblendite	HOR(hbld)	369.4 ± 0.7
Biotite hornblende granite	29 (bio)	187.0 ± 6

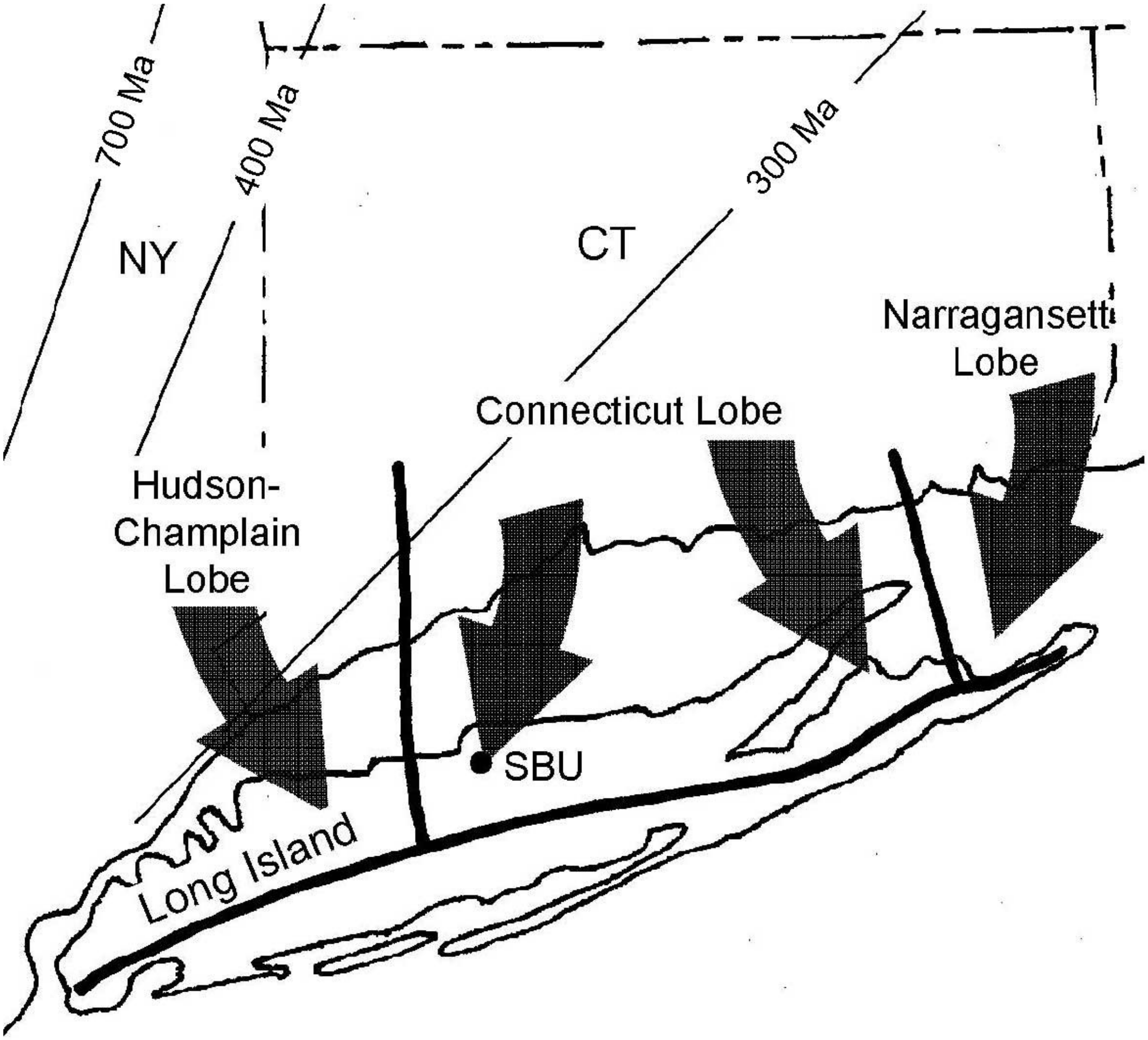

Fig. 3 Map showing the three glacial lobes extending to Long Island (Isachsen *et al*, 1991) and contours of Ar-Ar and K-Ar ages for biotite and muscovite (Zhong, 2002) in Connecticut and eastern New York. Rarely does muscovite have ages greater than 400 Ma. The ages greater than 700 Ma for biotite are in the Grenville Province terrane

The Stony Creek type rocks have peaks at roundness of 0.3 and 0.6. Stony Creek type boulders are more common on the eastern part of the Stony Brook campus. Stony Creek type boulders are absent at Crane Neck beach which is 4.5 miles north-northwest of the campus. These observation suggest a more easterly source for the Stony Creek type boulders.

The Branford foliated and massive quartz monzonites have similar distributions of roundness, which suggests that they come from the same area. Combined Branford type rocks peak at roundness classes of 0.3 and 0.5. The numbers of boulders with a roundness of 0.3 is less than one-half the number of boulders in the 0.5 class. This would suggest that there was large area of exposed outcrop of Branford type basement northwest of the basin in Long Island Sound and a smaller area of outcrop southeast of the basin. At the Crane Neck beach 4.5 miles to the north-northwest of the Stony Brook campus only Branford type boulders of Avalonian Terrane granitic rock types are found. At this location there are boulders up to 5 meters in diameter of Branford type rocks. On the Lewis Stone map there is no indication of basement between Crane Neck and the basin. However, the large angular boulders at Crane Neck suggest that basement cannot be too far offshore. Or, less likely the large boulders were carried englacially across the basin and then carried at the base of the glacier on their way to the Stony Brook campus. Based on the observation that Branford type quartz monzonite is common at Crane Neck beach and that the majority of the boulders of this type of rock are on the west side of the campus, it is probable that boulders of the Branford type quartz monzonite came from the north-north west.

The explanation for small number of Middletown Formation boulders would be an observation made by Mikami and Digman, 1957 less than 5% of the surface is covered by scattered inclusions of rocks from the Middletown formation.

SPHERICITY, SHAPE AND SIZE

The sphericity of the boulders has been calculated on the basis of Wadell's definition – the cube root of the ratio of the volume of the particle to the volume of its circumscribing sphere – with Krumbein's (1941) modifications wherein the volume of a particle was substituted for the volume of a triaxal ellipsoid calculated on the basis of three diameters of the particle.

For the Avalonian granites and gneisses a linear regression through a plot of roundness versus sphericity has an r^2 value of 0.13 and through the data on a plot of roundness versus volume has an r^2 value of 0.04. Thus, there is no correlation for sphericity, shape or size with roundness. This is reasonable considering that the original shape and size of the boulders would be expected to be highly variable dependent on the joint spacing of the basement rocks.

ROUNDNESS VERSUS DISTANCE

The morphology of the Stony Brook moraine suggests that there were at least three advances forming the western portion of the Stony Brook Moraine. Radii of the arcs of the moraines range from the northwest to north. Seventeen miles across LIS, in Connecticut are Paleozoic gneisses and schists of the Acadian Terrane. These lithologies make up only a small percentage of the boulders in the Stony Brook moraine. Eighty six per cent of the boulders are granite and gneiss of the Avalonian type terrane. Avalonian type rocks on the north shore of Long Island Sound in Connecticut are significantly east of the direction of the glacial paths of the sub-lobes that formed the Stony Brook moraine. Therefore, it can be inferred that the Avalonian Terrane underlies Long Island Sound north and northwest of Stony Brook. The occurrence of basaltic boulders with intermediate roundness is also consistent with the proposed extension of the Hartford Basin into Long Island Sound as indicated by extremely deep bedrock on Lewis and Stone, 1991, seismic reflection map (Fig.1).

Based on the extent of roundness and the basement outcrop map of Lewis and Stone, 1991, it should be possible to evaluate the average distance of travel of a boulder type at the base of a glacier and the extent to which the boulder type has been rounded. This estimate is made on the basis of the roundness of boulders, which have their sources on both sides of the basin in Long Island Sound. Roundness 0.3 corresponds to a distance of 6 miles to the nearest outcrop of Stony Creek type granite assuming that its source is immediately to the north and is on the southeast side the basin. A roundness of 0.5 corresponds to a distance of 12 miles to the possible outcrop of Branford-type quartz monzonite northwest of the basin. The valley in roundness near 0.4 for Branford type granite and quartz monzonite corresponds to the 9-mile distance to the middle of Hartford basin. These data would suggest that a change in roundness of 0.1 corresponds on average to a distance of about three miles (Fig. 5).

Assuming that there are basalts in the basin they should be on average about 9 miles from the Stony Brook Campus. The basalts have one sharp mode of roundness of 0.5 suggesting a limited source area. Granite boulders based on Fig. 4 be expected to have a roundness mode of 0.4 for this distance. This incongruence may be explained by fact that joints in basalt, whether in lava flows, dikes or sills, would produce blocks with high sphericity, *i.e.*, equal dimensions, and medium-size boulders which are easier to round. Also, basalt consisting dominantly of plagioclase and pyroxene might be expected to round more easily than granites with their relatively high quartz content.

Table 1 Roundness and number of each type of boulder studied. The modes are in

	Stony Creek-type	Stony Creek type pegmatite	Branford type	Branford type pegmatite	Beardsley type	Pumpkin Ground type	Basalt	Quartz
Number of Boulders	136	46	76	33	7	6	28	13
Roundness	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
0.1	3	2	1	3	**43**	0	4	8
0.2	15	0	13	3	**43**	**33**	0	**38**
0.3	**23**	**24**	**16**	21	14	17	21	0
0.4	19	18	13	**38**		17	**43**	**23**
0.5	14	22	**37**	24	0	17	18	8
0.6	**23**	**31**	16	6	0	17	14	**15**
0.7	3	2	4	3	0	0	0	8
0.8	1	2	0	3	0	0	0	0
0.9	0	0	0	0	0	0	0	0

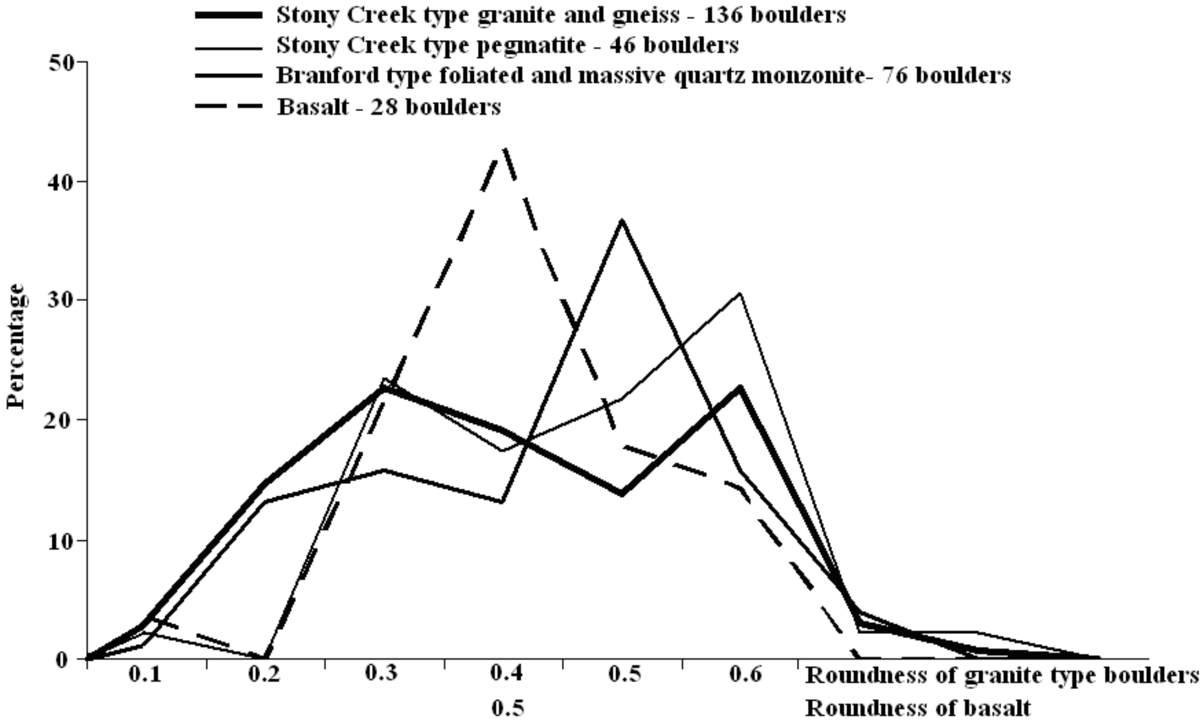

Fig. 4 Percentage of boulders at given roundness.

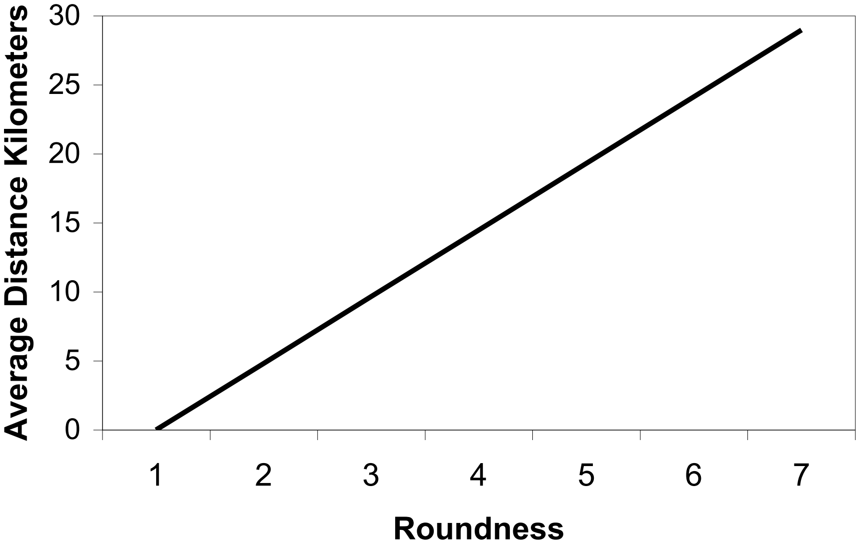

Fig. 5 Plot of distance versus roundness (x 10) assuming that the basalts are derived from the Triassic rift basin in Long Island Sound and that the minima in the roundness plots in Fig. 4 are due to the presence of the Triassic rift basin.

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