Office of the Massachusetts State Geologist
University of Massachusetts, Amherst

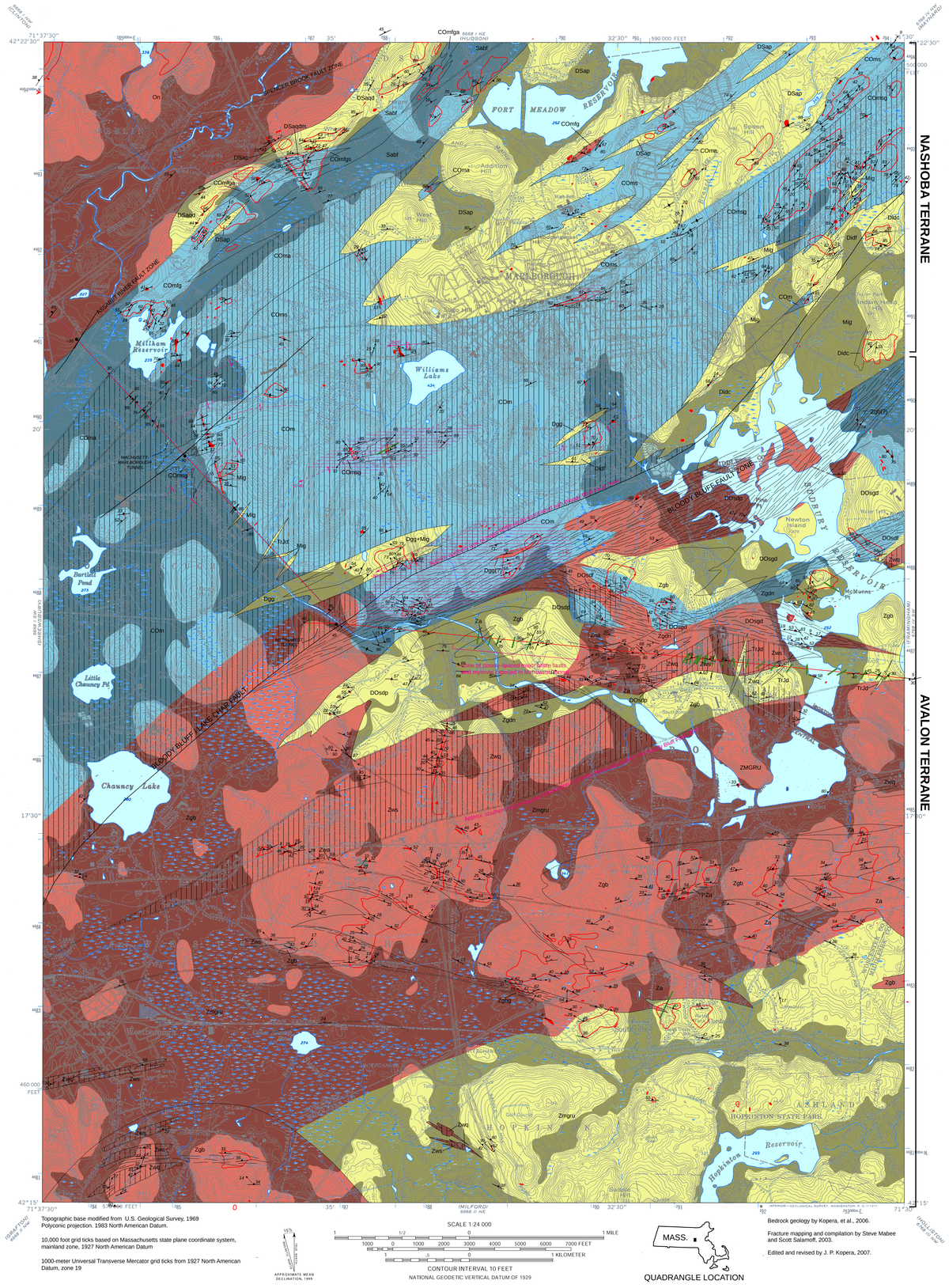
Address: 269 Morrill Science Center, 611 North Pleasant Street, Amherst, MA 01003
Phone: 413-545-4814 **E-mail:** sbmabee@geo.umass.edu
WWW: http://www.geo.umass.edu/stategeologist

Fracture Characterization Map of the Marlborough Quadrangle, Massachusetts: Hydro-Structural Domain Map (sheet 1 of 5)

by Stephen B. Mabee[1] and Scott A. Salamoff

Author Affiliations: [1]***Corresponding Author:*** Office of the Massachusetts State Geologist *E-mail:* sbmabee@geo.umass.edu

OMSG Geologic Map No. 06-02.1, Sheet 1
Fracture Characterization Map
Marlborough Quadrangle
2006 *(revised 2007)*



EXPLANATION OF HYDRO-STRUCTURAL DOMAIN UNITS

Massive Rocks - Rocks exhibiting no foliation or occasional weak foliation. This unit includes almost all intrusive rocks in the Nashoba terrane and several in the Avalon terrane. This unit is cut by two steeply-dipping, through-going joint sets trending 18° and 151°. Sheeting joints are prevalent in unfoliated granites of the Avalon terrane and strongly developed where observed. Sheeting was not observed in the Andover granite due to a lack of exposures but is expected to be present.

Moderately-Dipping Layered Rocks - Foliated rocks exhibiting dips of 30° to 60°. Includes many intrusive rocks of the Avalon terrane where the are foliated and/or sheared, the Westboro formation (Zwq, Zws), and Nashoba formation (On). This unit is cut by two steeply-dipping, through-going joint sets trending 18° and 151°. Sheeting is moderately to strongly developed in the granties of the Avalon terrane and less well developed in the Nashoba formation.

Steeply-Dipping Layered Rocks - Foliated rocks exhibiting dips greater than 60°. Includes rocks that have been sheared in the Bloody Bluff Fault Zone, the Marlboro formation, foliated Andover granite. Unit is cut by two steeply-dipping, through-going joint sets trending 18° and 151°. Sheeting is generally moderately well developed throughout and strongly developed along the Assabet River Fault.

Partings Parallel to Layering - Overlay pattern shows areas where outcrops have a moderate to strong tendency to part (open) parallel to dominant foliation. Partings are pervasive, generally through-going and generally extend across the outcrops. Spacing between partings are often less than 0.5 m and commonly less than 1.0 m. Many partings are open.

Permeable Surface Materials - Overlay shading shows areas where permeable and conductive overburden is observed at the surface and may lie above the bedrock.

EXPLANATION OF SYMBOLS

(modified from Kopera et al., 2006)

Exposure

- Bedrock outcrop examined in field
- Area of abundant outcrop or shallow bedrock (within 10 feet of surface)
- Alignment of subsurface tunnel data used in construction of map

Planar Features *(placed over location measured. Where many symbols present placed as close to outcrop as possible)*

- Strike and dip of foliation and vertical foliation in all rocks, composite S_1 foliation in the Marlborough formation, composite S_1 or later foliation in the Nashoba formation, and foliation of undetermined age in plutonic rocks. In all layered rocks foliation is dominantly parallel to bedding and/or compositional layering.
- Approximate strike and dip of heavily contorted foliation
- Strike and dip of secondary foliation and crenulation cleavage (S_2) in Marlboro Formation. This foliation generally parallels the axial surfaces of F_2 folds and cuts the S_1 foliation.
- Strike and dip of axial surface of secondary fold (F_2) of S_1 foliation in the Nashoba terrane (Photo 1), or fold of undetermined age in Avalon Terrane.
- Mylonitic fabric and/or shear fabric of undetermined age
- Fracture cleavage of undetermined age
- Brittle fault observed in outcrop or tunnel interpreted to be significant at map scale. For additional outcrop-scale brittle structure information, see Mabee and Salamoff (2006).

Linear Features

- Trend and plunge of mineral lineation of undetermined age
- Trend and plunge of axis of secondary fold (F_2) of S_1 foliation in the Nashoba terrane, or fold of undetermined age in the Avalon terrane

EXPLANATION OF LINES

- Contact-- Accuracy of location indicated by proximity to bedrock exposures. Contacts between units within the Marlboro Formation and Neo-Proterozoic plutonic rocks are generally gradational.
- Trace of discrete shear zone or sheared contact. Queried in Nashoba terrane where relations to Andover granite are unknown.
- Zone of sheared and cataclastic rocks
- Trace of brittle fault. Approximate dip shown where exposed in subsurface tunnel and/or outcrop. Only the traces of faults that can be supported by unequivocal field evidence are shown.
- Trace of axial surface of map-scale F_2 or later antiform showing plunge of axis, where estimated. Dashed where existence inferred.

EXPLANATION OF LITHOLOGIC UNITS

(modified from Kopera et al., 2006)

TrJd — DIABASE

NASHOBA TERRANE

Intrusive Rocks

INDIAN HEAD HILL PLUTON

- Mig — GRANITE
- Didc, Didf — DIORITE - Coarse-grained (Didc) and fine-grained (Didf)
- Dgg — GRANITE-GNEISS
- DSaqd, DSaqdm — ASSABET QUARTZ DIORITE - Mylonitized (DSaqdm)

ANDOVER GRANITE

- DSap — PEGMATITIC GRANITE
- Sabf — FOLIATED BINARY GRANITE

Areas of abundant granitic dikes and sills of undetermined age and affinity. Includes probable dikes and sills of Mig and Dgg.

Stratified Rocks

Stratified rocks in the Nashoba terrane have been metamorphosed under conditions of the mid- to upper amphibolite facies.

- On — NASHOBA FORMATION

MARLBORO FORMATION

- COmfg, COmfgs, COmfga — FELSIC GRANULITE AT MILLHAM RESERVOIR - with schist (COmfgs), and amphibolite (COmfga).
- COma, COms — AMPHIBOLITE (COms) AND SCHIST (COma)
- COmsg — SCHIST AND GRANULITE
- COm — UNIDFFERIENTIATED AMPHIBOLITE AND OTHER ROCKS

AVALON TERRANE

Paleozoic (?) Intrusive Rocks

SUDBURY VALLEY INTRUSIVE COMPLEX

- DOsdp, DOsdf — DIORITE - porphyritic (DOsdp) and fine grained (DOsdf)
- DOsgd — GABBRODIORITE

Neo-Proterozoic Plutonic rocks

Note: The Neo-Proterozoic plutonic rocks commonly contain small bodies of dark-greenish-gray, crumbly, fine-grained chloritized biotite amphibolite and biotite schist, up to 3 m in width interpreted to be altered mafic dikes or sills which are distinct from TrJd (Hepburn and DiNitto, 1978).

- Za — ALASKITE
- Zgdn — GRANODIORITE AT NOURSE FARM
- Zgb, Zgbg — BIOTITE-GRANITE AND GRANITE-GNEISS - Locally sheared to a biotite-magnetite gneiss (Zgbg).
- Zmgru — UNDIFFERENTIATED MILFORD GRANITE AND BIOTITE-POOR GRANITE

Stratified Rocks

WESTBORO FORMATION

- Zwq — QUARTZITE
- Zws, Zwa — SCHIST AND GREENSTONE - Schistose amphibolite (Zwa) occurs locally. Interbeds of Zwq are common.

HYDROLOGIC SIGNIFICANCE OF HYDRO-STRUCTURAL DOMAINS

Massive Rocks - The primary avenue for vertical recharge in this hydro-structural domain is through the steeply-dipping, 18°-trending fracture set with secondary leakage via the 151°-trending fracture set. The 18° fracture set is pervasive throughout the quadrangle with a median spacing of 0.25 m and median trace length of 1.64 m. About 43% of all fracture zones observed are parallel to this trend. Lateral connectivity in this unit is provided by sub-horizontal sheeting joints.

Moderately-Dipping Layered Rocks - The moderate dips (30° to 60°) in the layering provide good vertical recharge opportunities as well as enhanced lateral connectivity. The moderate dips may also allow recharge to the bedrock from surface waters and overburden deposits located updip and beyond local topographic divides. Vertical recharge is augmented by near-vertical 15°-trending fracture zones and the 18° and 151° fracture sets.

Steeply-Dipping Layered Rocks - The steep dips (>60°) in the layering provide good vertical connection with surface waters and overburden aquifers. Vertical recharge is enhanced by steeply dipping, 18° and 151°-trending fractures, 15°-trending fracture zones and associated outcrop-scale faults. Lateral connectivity is provided by sheeting joints which are generally well developed along the Assabet River Fault and in the Straw Hollow diorite.

Partings Parallel to Layering - Rocks showing a moderate to strong tendency to part (open) parallel to dominant foliation have excellent potential for vertical recharge. These areas are expected to demonstrate a strong flow anisotropy parallel to foliation under pumping conditions and are vulnerable potentially to surface contamination. Overburden wells and water bodies overlying these areas may experience water level reductions under pumping conditions.

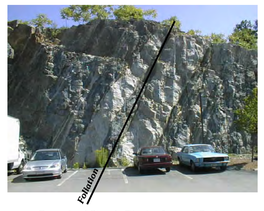
Permeable Surface Materials - Areas of permeable overburden may provide a source of recharge to the bedrock particularly in areas with steeply-dipping layering. This also includes swamps and other water bodies located within permeable overburden. Overburden wells located in these areas may experience water level reductions under bedrock pumping conditions. Water bodies, swamps and streams may also be affected by bedrock pumping with a potential impact to wetland and riparian ecosystems.

Example of Massive Rocks

Non-foliated granite in the Avalon terrane exhibiting strong sheeting development. Main cross joint set is 18°.

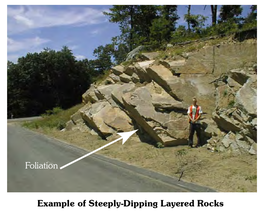
Example of Modetately-Dipping Layered Rocks

Moderately-dipping foliated granite in the Avalon terrane showing strong parting parallel to foliation (<1 m spacing). Main cross joint set is 18°.



Example of Steeply-Dipping Layered Rocks

Foliated Marlboro formation with light-colored Indian Head Hill granite intruding parallel to foliation. Partings parallel to foliation are moderately well-developed.



Example of Steeply-Dipping Layered Rocks

Foliated binary Andover granite showing three well-developed fracture sets. Partings parallel to foliation are strongly developed.
Rock breaks into characteristic rhombohedral blocks.

Example of Sheeting Joints

Strongly-developed (less than 1 m spacing) sheeting joints in foliated diorite. Joints are transmissive.

DISCUSSION

INTRODUCTION

The Hydro-Structural Domain Map is a summary map that represents the synthesis of 3066 brittle fracture measurements collected at 68 outcrops distributed across the quadrangle. The units and overlay zones shown on the map define regions that contain attributes thought to be important in influencing groundwater availability and flow in the bedrock. These attributes include bedrock type, the presence or absence of layering (foliation) in the rocks, the degree of development of transmissive partings parallel to the layering, the intensity of sub-horizontal sheeting development, the number and distribution of regional joint systems and outcrop-scale faults, and the distribution of permeable surface materials. The raw data from which this summary map was assembled are summarized in Appendices A-D.

GENERAL GEOLOGY

The rocks of the Marlborough quadrangle have been described previously by Barosh (1978), Bell and Alvord (1976), Castle et al. (1975), Hepburn and DiNitto (1978), Skehan and Abu-Moustafa (1976), DiNitto (1983) and Kopera et al., (2006). Precambrian to Mississippian intrusive and metamorphic rocks underlie this area. Deformed and metamorphosed volcanic rocks of the Marlboro Formation and volcanoclastic rocks and pelites of the Nashoba Formation underlie the northern two-thirds of the area. These rocks are intruded by the Straw Hollow diorite, Indian Head Hill pluton and Andover granite. The southern third of the area is underlain by Neo=Proterozoic granites and the Westboro Formation. Two major structures traverse the area: the Bloody Bluff Fault zone, which forms the boundary between the Nashoba terrane to the north and the Avalon terrane to the south and the Assabet River fault zone in the northwest. Both faults exhibit highly sheared and altered rocks.

FRACTURE CHARACTERIZATION

Joints and Outcrop-Scale Faults

The steeply-dipping (dips >60°), 18°±17°-trending joint set is the dominant joint set in the area. It is spatially pervasive, penetrative, crosscuts foliation and is commonly observed to be open and transmissive. Approximately 43% of all fracture zones (closely-spaced fractures that occur in a zone with finite width) and 23% of all macrojoints (joints with trace lengths >5 m) parallel this joint set. Thus, these features are important avenues for vertical recharge and may appear as fracture traces or lineaments on aerial photographs.

Secondary joint sets include the 151°±16° and 241°±17° sets. The 151° set is orthogonal to the regional strike of the geology and thus is an important cross cutting feature. The 241° joint set parallels regional foliation. It is pervasive north of the Bloody Bluff Fault zone but is less common in the granites of the Avalon terrane to the south.

Two other minor joints sets also occur, 173°±5° and 90°±15°. The 173° set is most readily observed along a one-mile strip along the I-495 corridor. The 90° joint set is weakly developed and sparsely distributed.

Median spacing of all fractures is 0.3 m (n=1943) and median trace length is 1.3 m (n=2427). The 18° joint set has slightly closer spacing with a median spacing of 0.25 m. Outcrop-scale faults occur in four groups: NNE-trending, which correspond with the 18° regional joint set, NE-trending, which correspond with foliation, east-west and NNW. East-west trending ductile shear zones are most common in the granites of the Avalon terrane.

Foliation and Sheeting

Foliation development occurs in three distinct zones. South of the Bloody Bluff Fault zone foliation is dominantly east-west and dips moderately (30° to 60°) to the north. Between the Assabet River and Bloody Bluff Faults, the foliation trend becomes northeast and the dip steepens to generally greater than 60° NW. Northwest of the Bloody Bluff the dip shallows to 30° and 60° and the strike becomes more NNE. Overall, steeper foliation dips are observed in the north, whereas shallower dips are observed in the south. Dip angles also steepen proximal to faults and become shallower distal to faults. The potential for water transmission is enhanced in those zones where foliation exhibits a moderate to strong tendency to part parallel to foliation. These areas occur most commonly in the amphibolites, portions of the Indian Head Hill pluton and foliated portions of the granites of the Avalon terrane and Andover granites.

Sub-horizontal sheeting is prevalent throughout the area but is best developed in the massive igneous rocks, foliated granites and metamorphic units exhibiting foliation dips of greater than 49°. Median spacing of sheeting joints is 0.3 m and median trace length is 2.1 m. Sheeting trajectories are mainly east west south of the Bloody Bluff Fault zone paralleling the east west foliation. North of the Bloody Bluff Fault sheeting trajectories are more northeast and follow the northeast trending topography. Partings parallel to sheeting joints are most strongly developed along the Assabet River Fault, Indian Head Hill granite, Westboro Formation, granites of the Avalon terrane, Andover granite and more amphibolitic portions of the Marlboro Formation. In general, sheeting joints are most strongly developed in the granites.

Summary of Hydrologically Significant Features

The dominant water-bearing features observed in the area are: 1) the 18° regional joint system, 2) Sub-horizontal sheeting joints, 3) areas exhibiting strong to moderate partings parallel to foliation, 4) cataclasite-cored brittle faults, and 5) locally important extensional cross fractures. Partings parallel to foliation are strongly developed, open and transmissive dominantly in the granites and amphibolites. Foliated granites provide the most consistent, orthogonal networks of interconnected fractures. Calcite mineralization and iron staining is common throughout the area. Sulfide mineralization was observed proximal to the Assabet River Fault and in outcrops of Westboro Formation and Neo-Proterozoic granite in the Avalon terrane along I-495 and the Massachusetts Turnpike. These areas may produce localized pockets of poorer water quality in bedrock wells.

REFERENCES CITED

Barosh, P.J., 1978, Reconnaissance bedrock geologic map of the Marlborough quadrangle, Massachusetts: U.S. Geological Survey Open-file Report 78-221, 17p., 1 pl., scale 1:24,000.

Bell, K.G. and D.C. Alvord, 1976, Pre-Silurian stratigraphy of northeastern Massachusetts: Geological Society of America Memoir 148, pp. 179-216.

Castle, R.O., H.R. Dixon, E.S. Grew, A. Griscom, and I. Zietz, 1975, Structural dislocations in eastern Massachusetts: U.S. Geological Survey Bulletin 1410, 39p.

Hepburn, J.C. and R.G. DiNitto, 1978, Preliminary bedrock geologic map of the Marlborough quadrangle, Middlesex and Worcester Counties, Massachusetts: U.S. Geological Survey Open-file Report 78-222, 29p., 1 pl., scale 1:24,000.

Skehan, J.W. and A.A. Abu-Moustafa, 1976, Stratigraphic analysis of rocks exposed in the Wachusett-Marlborough tunnel, east-central Massachusetts: *in* Page L.R., ed., Contributions to the stratigraphy of New England, Geologic Society of America Memoir 148, pp. 217-240.

DiNitto, R.G., 1983, The bedrock geology of the Marlborough area, Massachusetts: M.S. Thesis, Boston College, 217 p.

Kopera J., DiNitto R., and Hepburn J.C., 2006, Bedrock geologic map of the Marlborough quadrangle, Office of the Massachusetts State Geologist Geologic Map 06-01. Scale 1:24,000. 1 sheet and digital product: Adobe PDF and ESRI ArcGIS database.

This research was supported by U.S. Geological Survey, National Cooperative Geologic Mapping Program, under assistance Award No. 03HQAG0067 and an NSF REU Grant to the Association of American State Geologists. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government, the Commonwealth of Massachusetts, or the University of Massachusetts.

Citation:

Mabee, S.B. and S. Salamoff, 2006, Fracture characterization map of the Marlborough quadrangle, Office of the Massachusetts State Geologist Geologic Map 06-02. Scale 1:24,000. 5 sheets and digital product: Adobe PDF and ESRI ArcGIS database.

A digital copy of this map, including GIS datalayers, is available at **http://www.geo.umass.edu/stategeologist**. Additional paper copies can also be obtained from the Office of the State Geologist for a small fee.