BURIAL AND HYDROTHERMAL DIAGENESIS OF THE SANDSTONES IN THE EARLY MESOZOIC DEERFIELD RIFT BASIN, MASSACHUSETTS

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ABSTRACT: The burial and hydrothermal diagenesis that affected the sandstones in the Deerfield rift basin is interpreted using field mapping, thin-section modal analyses, X-ray diffraction, SEM imaging, microprobe analyses, $^{40}Ar/^{39}Ar$ thermal analyses of individual detrital microcline crystals, and biomarkers. During burial diagenesis, albite and quartz overgrowths were ubiquitous early cements, co-precipitated from downward-circulating groundwaters driven by topographic relief around the basin. Beginning about 201 Ma, in earliest Jurassic time, increased rates of crustal extension led to melting of the upper mantle and extrusion of the Deerfield lavas. High heat flow due to crustal extension peaked at about 184 Ma, producing a deep-basinal, hot brine. Soaking in the brine and rising hydrothermal plumes generated four patterns of diagenetic minerals superimposed on the early burial cements: illite; mosaic albite; bleached mosaic albite; and chert-illite-pyrite. Biomarker data show that the lacustrine gray/black mudstones are thermally overmature for hydrocarbons, in and beyond the "gas window."

Argon spectra for detrital microclines in the Sugarloaf Arkose are compatible with gradual cooling of the basin through about 150°C at about 170-150 Ma. The spectra also indicate cooling through 300-350°C at 290-270 Ma, confirming Late Paleozoic metamorphism of the Lower Paleozoic source rocks east of the basin.

INTRODUCTION

The Deerfield basin of Late Triassic-Early Jurassic age is one of the rift basins of the Newark Supergroup along eastern north America that formed during breakup of Pangea. As the basin drifted northward in the tropics from approximately paleolatitude 4° to 8°N (Olsen 1997), it filled with about 4-km of terrestrial strata and basaltic lavas (Figs. 1 and 2). The Deerfield Basalt and the other lava-flow units in the Newark Supergroup are dated at 201± 2 Ma (Sutter 1988; Thompson 1998; Dunning and Hodych 1990; Turrin and Hemming 2000). In the Deerfield basin the oldest unit is the 1.7-km Sugarloaf Arkose composed of fluvial redbeds deposited during early sagging of the basin floor. In earliest Jurassic time, increased rates of crustal extension and thinning produced a shift from an open to closed basin architecture, formation of the west-dipping, listric normal fault on the east side of the basin, and extrusion of basaltic lava flows (Hubert and Dutcher 1999). The result was an angular unconformity on the Sugarloaf Arkose, followed by the 9-m Fall River beds of lacustrine and marsh origin, and then the 50-100-m of the Deerfield Basalt, extruded as two lava flows. In the closed basin, the 2-km of the Turners Falls Formation then accumu-

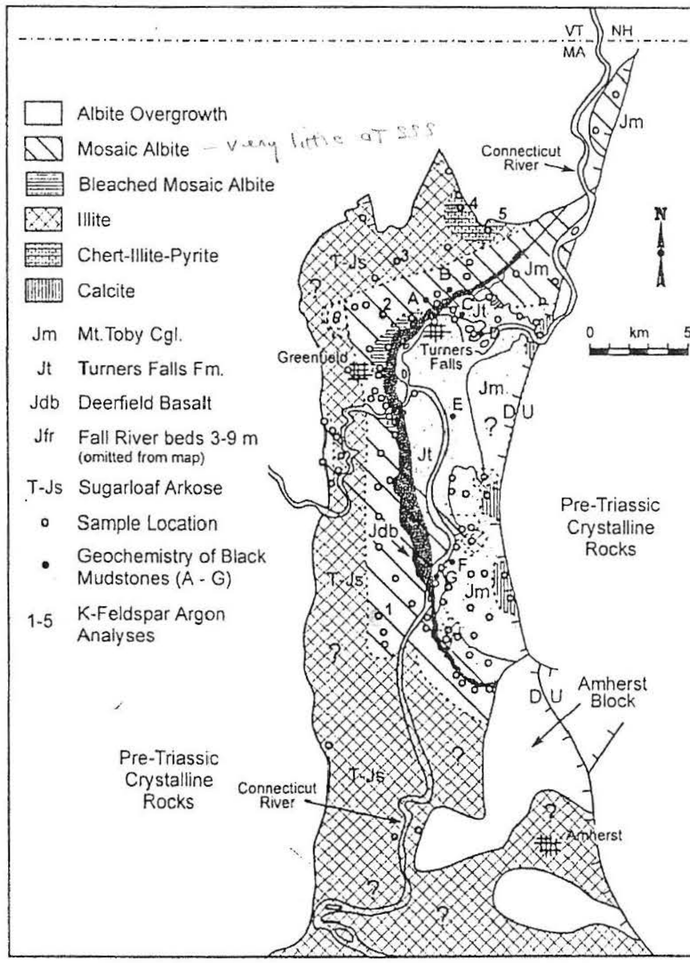

Figure 1. Diagenetic patterns in the sandstones in the Deerfield basin. Geologic map after Olsen et al.(1992). The locations for K-feldspar argon analyses are 1) SF-SR5E, 2)SF-G9B, 3) SF-I91-A4D, 4) SF-FR3A, and 5)RS-161A (Fig. 12).

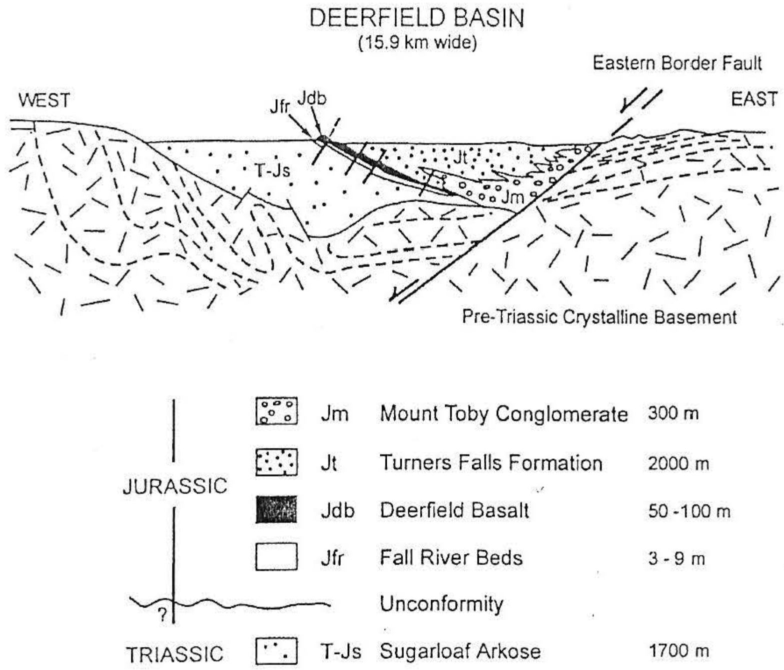

Figure 2. West-east cross section of the Deerfield basin, Massachusetts, at about the latitude of the town of Greenfield (modified from Wise et al. 1992).

lated as cycles of playa redbeds and lacustrine gray-black strata controlled by Milankovich-climate forcing, plus minor fluvial redbeds. The 300-m Mount Toby Conglomerate, in part laterally equivalent to the Turners Falls Formation, consists of alluvial-fan deposits shed from the fault-bounded eastern highlands. On the geologic map of Massachusetts (Zen et al. 1983), the Triassic-Jurassic boundary is drawn 100 m below the top of the Sugarloaf Arkose to match the spores and pollen of Hettangian age in the Fall River beds.

In the Deerfield basin the "normal" burial diagenetic cements were overprinted by diagenetic minerals precipitated during a hydrothermal event, which also affected the Hartford basin (Merino et al. 1997). The two basins can be considered sub-basins of a single basin (Schlische 1995). In the Deerfield basin, we mapped six diagenetic patterns in the sandstones (Fig. 1). The initial pattern is co-precipitation of quartz and albite overgrowths during burial diagenesis from topographically-driven, downward-moving groundwaters. Increased rates of crustal extension in earliest Jurassic time produced substantially higher rates of heat flow, melting of the upper mantle, and extrusion of the Deerfield lavas. The heating made the basin overmature for hydrocarbons and produced a deep-basinal brine. *In situ* soaking of the sandstones in the brine and rising hydrothermal plumes superimposed four hydrothermal patterns on the albite-overgrowth pattern: mosaic albite; bleached mosaic albite; illite; and chert-illite-pyrite. In highly fractured outcrops of the Mount Toby Conglomerate near the eastern border fault, calcite has filled pores and replaced grains in the sandy conglomerates, forming the calcite pattern.

This paper documents the diagenetic patterns in the sandstones and reconstruct the thermal history of the basin, using field mapping, 125 thin-section modal analyses, X-ray diffraction, SEM imaging, microprobe analyses, $^{40}Ar/^{39}Ar$ thermal analyses of individual detrital microcline crystals, and biomarkers.

FIELD AND LABORATORY METHODS

Thin-section Modal Analyses.-- From throughout the Deerfield basin, 175 sandstones were collected from the Sugarloaf Arkose, Turners Falls Formation, and Mount Toby Conglomerate, covering the fluvial, lacustrine, playa, and alluvial-fan facies. The distribution of sample locations reflects outcrop availability, which is good everywhere except in the northwestern and southern parts of the basin.

Before cutting thin sections, sandstone "heels' were impregnated with blue-dyed epoxy to preserve pore spaces. The thin sections were stained with sodium cobaltrinitrite to distinguish K-feldspar from untwinned plagioclase; potassium ferricyanide and Alizarin red-S stains differentiated among carbonates (Friedman 1971). The volume proportions of the petrographic constituents were determined by counting 300 points per thin section, using standard definitions for the petrographic constituents (e. g., Hubert et al. 1992). The data base comprises 125 modal analyses of sandstones: 64 from the Sugarloaf Arkose, 27 from the Turners Falls Formation, and 34 from the Mount Toby Conglomerate. These data include 10 sandstones from the Turners Falls Formation from Meriney (1988). Tables of the modal analyses are available in Taylor (1991).

X-ray Diffraction Analyses.--Diagenetic clay matrix was separated from the sandstones by the following procedure. 1) The sample was lightly crushed to mm-size pieces in a mortar and pestle. 2) The pieces were added to a solution of 29.5 ml of Miramine Oc (liquid soap, pH = 12) per 400 ml hot water, sonified for 1 minute, and stood overnight to disaggregate. 3) The sample and solution were resonified, then wet-sieved through a 2.5-phi sieve to remove larger grains. The <2.5 phi fraction was processed following standard procedures for X-ray diffraction analysis of oriented and randomly oriented mounts.

To isolate the diagenetic chlorite present in some sandstones in the bleached mosaic-albite pattern, mm-size pieces of sandstone were crushed in a mortar and pestle. The powder was run through a Franz isodynamic separator at a right-left angle of inclination of 25° and a current of 0.75 amps to concentrate magnetically the chlorite, which was then prepared for X-ray diffraction analysis by standard methods.

Minerals were separated from selected veins, crusted in a mortar and pestle, powdered in a specs-mill, then mixed with acetone and spread on glass slides for random-orientation study, using a Norelco X-ray diffractometer and Cu K α radiation.

SEM Images.-- Mm-size pieces of sandstone were imaged by scanning electron microscopy after being mounted with silver paste on aluminum stubs and sputter-coated with gold-palladium for 90-120 seconds. The images were taken at 20 Kv on a JOEL JSM-35CF system with a Tracor-Northern energy dispersive system at Mount Holyoke College, Massachusetts.

Microprobe Analyses.--The composition of the detrital feldspars and diagenetic minerals were determined by microprobe analysis and energy dispersive spectra at the University of Massachusetts, using a Cameca SX50 electron microprobe set at an accelerating potential of 15 kev, sample current of 15 nA, and beam diameter of 2-3 microns. Throughout the basin fill the detrital plagioclase grains are mostly oligoclase. The diagenetic plagioclase is nearly pure albite, whether overgrowths, mosaics, or replacement of detrital feldspar.

$^{40}Ar/^{39}Ar$ Analyses of Detrital Microclines.-- Using petrographic thin sections, sandstones containing large, unaltered microcline crystals were selected from the mosaic albite and chert-illite-pyrite patterns. Five of these samples were sawn into 3-mm-thick slices and then disaggregated to release >10 mm^3 crystals of microcline. Individual crystals were then cleaned with alcohol and broken up with mortar and pestle. A fraction of each crystal was used for X-ray diffraction characterization of the crystal with a Scintag/USA Dma 2000 diffractometer. A quantitative analysis of the proportion of contaminants, such as micaceous inclusions, in each crystal was based on the X-ray diffraction results and used to select the most pure microcline for analysis.

Each sample analyzed comprises broken parts of single crystals of microcline. For irradiation, the crystal fragments were individually wrapped in Al foil. Interspersed among the samples were aliquots of the flux monitor, the hornblende standard MMhb-1, with an age of 520 ± 2 Ma (Samson and Alexander 1987). The entire package was shielded with Cd and irradiated in the McMaster University nuclear reactor. An internal tantalum resistance furnace of the double-vacuum type was used to carry out the step-heating. All isotopic analyses were made in a VG 3600 mass spectrometer, using both Faraday and electron-multiplier collectors.

Although some controversy exists about detailed modeling of $^{40}Ar/^{39}Ar$ ratios in K-feldspar based on concerns of multiple diffusion domains in the feldspar (e.g., Parsons et al. 1999), numerous studies show that detrital K-feldspar can provide consistent information about the cooling history of rocks within the temperature range of about 125-350°C and thus can reconstruct the timing of metamorphism in source terrains and the thermal histories of basins (e. g., Reynolds et al. 1995; Krol 1996).

Biomarkers.-- Ten lacustrine gray/black mudstones from three localities in the Turners Falls Formation were analyzed for Rock-Eval pyrolysis, total organic carbon, and organic petrology in the laboratories of Texaco Oil Company (Table 1). The localities (Fig. 1) extend across the basin from south to north: 1) Montague just north of the railroad tracks between the fish hatchery and the Connecticut River, 2) North Sunderland west of Whitmore Pond along the stream that empties into the Connecticut River, and 3) below the dam on the Connecticut River at Turners Fall.

During Rock-Eval pyrolysis, three main pulses of pyrolysis products are recorded. S_1, the first peak, is the quantity of free, light hydrocarbons (HC) distilled off at temperatures below 300°C, in mg HC/g of mudstone. S_2 is the quantity of HC produced by thermal cracking (pyrolysis) of kerogen and high molecular weight bitumens at temperatures between 300-500°C, in mg HC/g of mudstone. S_3 is the quantity of CO_2 generated from kerogen concomitant with HC generation below 390°C in mg CO_2/g of mudstone. PI, the production index, is the ratio of $S_1/(S_1 + S_2)$. T_{max} is the temperature at which the maximum S_2 peak (maximum yield) occurs. TAI is the thermal alteration index based on the color of amorphous material. Ro is vitrinite reflectance. HI, the hydrogen index, is mg of generated HC/g of organic carbon. OI, the oxygen index, is mg of CO_2/g of organic carbon.

BULK COMPOSITION OF THE SANDSTONES

In the Sugarloaf Arkose, the proportions of quartz-feldspar-rock fragments among the framework grains, omitting cements and matrix < 0.03 mm, were plotted for 64 fluvial sandstones from the Sugarloaf Arkose on the classification

Table 1. Biomarker data for lacustrine gray/black mudstones in the Turners Falls Formation. Locations from south to north (Fig. 1) are M) Montague, NS) North Sunderland, and TF) along the Connecticut River below the dam at Turners Falls. Refer to Biomarkers in Field and Laboratory Methods for definitions of the quantities measured.

Sample	1	2	3	4	5	6	7	8	9	10
Location	M	M	M	M	M	M	NS	NS	TF	TF
TOC	1.62	1.24	0.68	1.02	1.42	1.10	1.37	1.13	0.49	0.44
S_1	0.04	0.03	0.07	0.01	0.01	0.02	0.35	0.17	0.09	0.13
S_2	0.13	0.09	0.25	0.02	0.04	0.03	0.25	0.13	0.05	0.06
S_3	0.34	0.32	0.35	0.01	0.00	0.04	0.10	0.08	0.04	0.04
S_1+S_2	0.17	0.12	0.32	0.03	0.05	0.05	0.60	0.30	0.14	0.19
PI	--	--	--	0.5	0.25	0.50	0.58	0.57	0.64	0.72
T_{max}	--	--	--	--	--	--	472	456	--	--
TAI	3	3	3	3.4-3.6	3.2-3.4	3.2-3.4	3.2-3.4	3.4-3.6	3.4-3.6	3.4-3.6
R_o	1.67	1.46	1.73	--	--	--	--	--	--	--
HI	8	7	37	1	2	2	18	11	10	13
OI	21	26	52	0	0	3	7	7	8	9

triangle of Folk (1968; Fig. 3). Excluding sandstones overprinted by the hydrothermal illite pattern, the average sandstone is an arkose. As the proportions of schist grains increase, the arkosic sandstones pass into lithic arkoses and a few feldspathic litharenites. In sandstones not affected by hydrothermal diagenesis, the plagioclase to K-feldspar ratio among framework grains is about 4.5 to 1. Ten of the 12 sandstones from the illite pattern are quartz-rich, namely quartzarenite, subarkose, and sublitharenite, reflecting widespread dissolution of plagioclase grains during precipitation of illite.

In the Turners Falls Formation, depending on the proportions of feldspar and schistose grains, the compositions of 27 playa, lacustrine, and fluvial sandstones in the Turners Falls Formation vary from arkose to litharenite, averaging lithic arkose (Fig. 4). In contrast to the sandstones in the illite pattern where plagioclase grains were mostly dissolved away, the sandstones with mosaic albite retained their plagioclase grains during precipitation of interstitial albite.

In the Mount Toby Conglomerate, 13 granule-pebble conglomerates from alluvial fans contain substantial amounts of metamorphic fragments and thus are feldspathic litharenites and litharenites (Fig. 5). In contrast, the fluvial sandstones are finer grained with fewer metamorphic fragments and comprise nine arkoses, ten lithic arkoses, and two feldspathic litharenites.

DESCRIPTION OF THE DIAGENETIC PATTERNS IN THE SANDSTONES

Petrographic modal analyses combined with field mapping established six diagenetic patterns in the sandstones (Fig. 1). The map patterns cross the boundaries of the fluvial, alluvial-fan, lacustrine, and playa facies, demonstrating that the patterns formed independently of depositional environments (Fig. 6). Some diagenetic minerals, not used to define the patterns, were precipitated from local groundwater in specific environments; for example, dolomite was precipitated in lacustrine and playa sandstones from shallow, alkaline groundwater with high ratios of Mg:Ca.

Albite-overgrowth

The albite-overgrowth pattern is widespread in the central and eastern parts of the basin in the Turners Falls Formation and Mount Toby Conglomerate, and is present at one locality in the Sugarloaf Arkose (Figs. 1, 6). Any of the other five patterns may contain albite overgrowths, but the overprinting diagenesis takes precedence in naming the pattern.

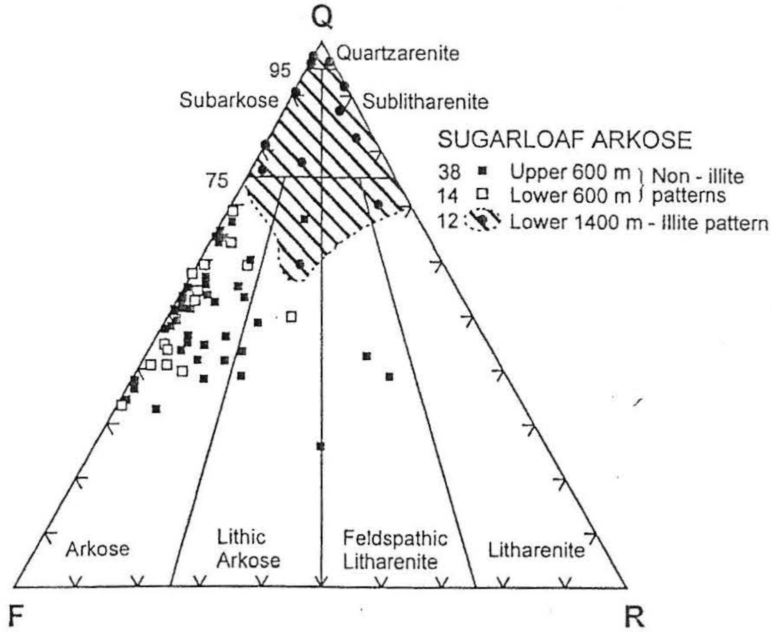

Figure 3. Compositions of the framework grains of 64 fluvial sandstones in the Sugarloaf Arkose, omitting cements and muddy matrix <0.30 mm. The triangle poles are quartz, feldspar and rock fragments (Folk 1968). Sandstones in the illite diagenetic pattern are relatively quartzose due to dissolution of plagioclase grains during precipitation of illite.

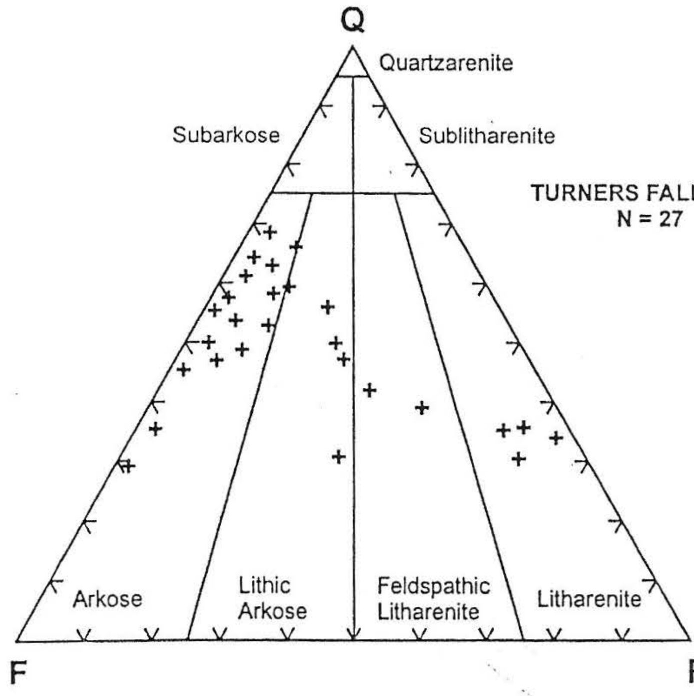

Figure 4. Compositions of the framework grains of 27 playa, lacustrine, and fluvial sandstones in the Turners Falls Formation plotted on the Folk (1968) classification.

In the albite-overgrowth pattern, albite overgrowths average 5 % of the volume of the sandstones, with a maximum 13 %. Microprobe analyses give an average composition of $Ab_{99.69}An_{0.08}Or_{0.23}$ (Meriney 1988). Where large pores were present, the overgrowths are larger, reaching 0.013 mm in maximum thickness. Overgrowths can be present on grains of plagioclase and K-feldspar. Many overgrowths contain tiny vacuoles, which decrease in abundance away from the host

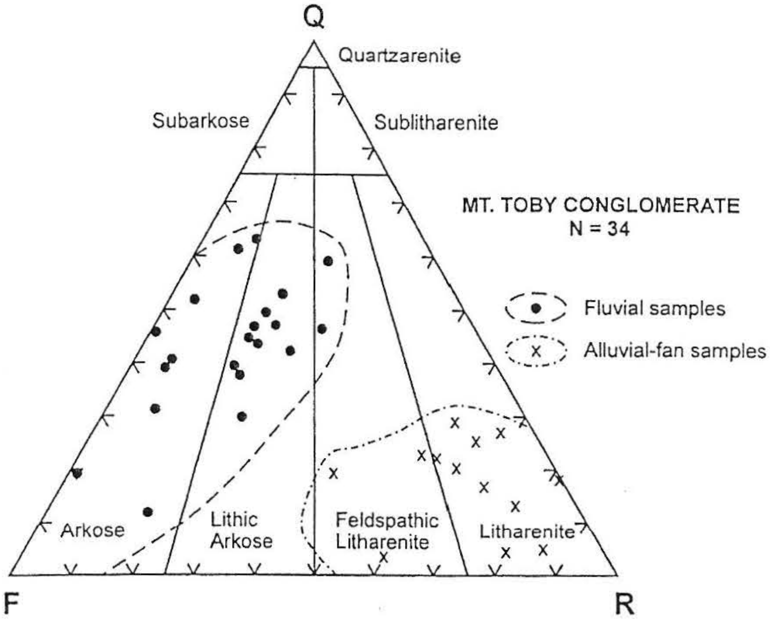

Figure 5. Compositions of the framework grains of 34 fluvial and alluvial-fan sandstones and granule-pebble conglomerates in the Mount Toby Conglomerate plotted on the Folk (1968) classification. The coarser samples are from alluvial-fan sequences and contain a higher proportion of schist grains.

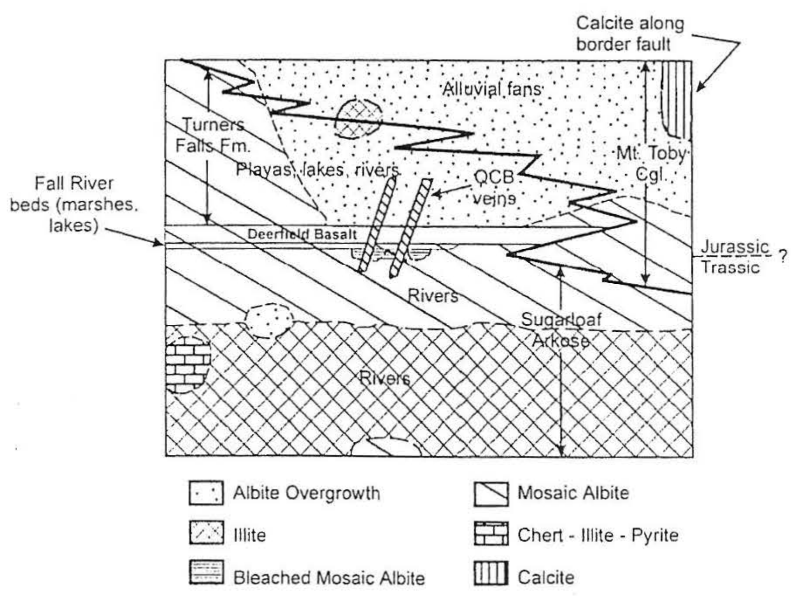

Figure 6. Generalized, schematic west-east cross section of the Deerfield basin showing: 1) the five formations; 2) the depositional environments of river, alluvial-fan, playa, lake, and marsh; and 3) the diagenetic patterns in the sandstones. The hydrothermal patterns (mosaic albite; bleached mosaic albite; illite; chert-illite-pyrite) were generated by a deep-basinal hot brine and cut formations and depositional environments.

grain (Fig. 7A). The overgrowths on twinned plagioclase grains can also be twinned, but sharpness of the twinning decreases away from the host grain. The degree of optical continuity varies between albite overgrowths and host plagioclase grains, evidently becoming closer as the amount of sodium in a host grain increases to match the overgrowth (Helmold et al. 1984). Some overgrowths are not a single crystal, but a group of syntaxial crystals that grew

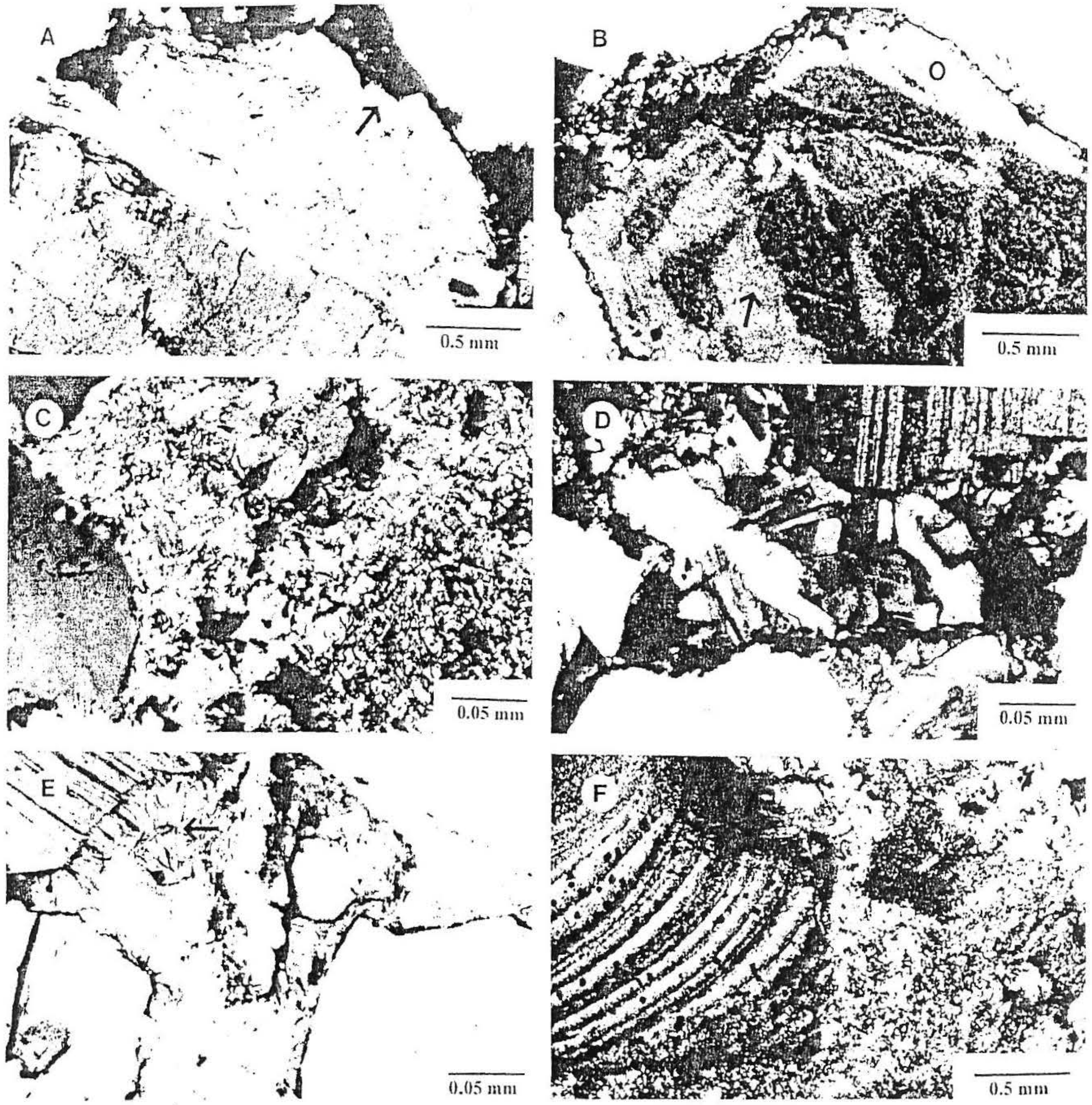

Figure 7. Thin-section photomicrographs of diagenetic features in the sandstones. A). Large albite overgrowth (arrow) on plagioclase grain in a Mount Toby sandstone in the albite-overgrowth pattern. Crossed Nicols. B). Partially albitized K-feldspar grain in a Sugarloaf sandstone in the mosaic albite pattern. Light gray albite (arrow) replaced K-feldspar along cleavages and fractures and is in optical continuity with the albite overgrowth (O). The replacement albite has a cloudy appearance due to minute dissolution vacuoles. Crossed Nicols. C). Diagenetic illite in a Sugarloaf sandstone in the illite pattern. Illite filled grain interstices and replaced a plagioclase (?) grain (lower right corner). Crossed Nicols. D). Interstitial microcrystalline mosaic albite in a Sugarloaf sandstone. The albite mosaic overlies hematite rims around the grains. Crossed Nicols. E). High-temperature, type-2b, diagenetic chlorite (arrow) in a Sugarloaf sandstone in the bleached mosaic albite pattern. Plain light. F). Chert pseudomorph of plagioclase (?) grain from a Sugarloaf sandstone in the chert-illite-pyrite pattern. The curved "fronts" of silica are evidently due to step-wise, progressive plagioclase dissolution accompanied by chert precipitation. The dark specks in the chert pseudomorph are pyrite. Diagenetic chert surrounds the grains. Crossed Nicols.

perpendicular to the surfaces of the host grains. Compromise boundaries between albite, quartz and K-feldspar overgrowths suggest that precipitation was coeval, although locally quartz precipitated on top of albite overgrowths.

Quartz overgrowths average 2 %, with a high of 9 %. Minor local cements are K-feldspar overgrowths on K-feldspar and plagioclase grains (particularly in the lower part of the Mount Toby Conglomerate), low-temperature chlorite, anatase, pyrite, and bitumen. Calcite, ferroan calcite, and less commonly ferroan dolomite, are widely distributed, locally abundant cements in the fluvial sandstones, generally younger than the albite and quartz overgrowths.

In the lacustrine and playa sandstones in the Turners Falls Formation, ferroan dolomite commonly precipitated earlier than albite and quartz. Some of these sandstones have 20-30 % total cements, implying cementation before substantial compaction.

Locally in the Mount Toby Conglomerate, traces to 4 % chlorite are the initial cement, accompanied by up to 4 % detrital biotite flakes. Post-deposition dissolution of biotite may have provided the iron needed to form the chlorite.

Analcime was only observed in a few granule conglomerates in the Mount Toby Conglomerate. Euhedral analcime crystals up to 0.3 mm in size grew on detrital grain surfaces within pores, followed by precipitation of calcite crystals. The surfaces of the analcime crystals lack hematite-stained mud, suggesting only a brief interval between precipitation of analcime and calcite.

Albitized grains of plagioclase, K-feldspar and perthite are fairly common in the Sugarloaf sandstones and are present locally in the Turners Falls Formation and Mount Toby Conglomerate. Most albitized grains have albite overgrowths, and albitization proceeded inward from the surface of the host grain along cleavage and fracture planes, producing domains of replacement albite in or close to optical continuity with the overgrowth (Fig. 7B). The replacement albite is commonly cloudy with tiny dissolution vacuoles. Albitization is best developed in sandstones where the host grains have thick albite overgrowths and relatively thin coatings of iron-oxides. Completely albitized plagioclase grains are recognized by their optically clear appearance and optical continuity with albite overgrowths. Replacement albite with "chessboard twinning" is rare.

Mosaic Albite

Mosaic albite is pervasively present in the upper part of the Sugarloaf Arkose above the illite pattern. It also occurs in three areas above the Deerfield Basalt, extending stratigraphically through the Turners Falls Formation and into the Mount Toby Conglomerate (Fig. 1). The pattern is defined by interstitial mosaics of albite crystals, whose presence takes precedence in naming the pattern over 1) albite and quartz overgrowths, which are commonly present, or 2) diagenetic illite. There is a notable separation of sandstones with mosaic albite from those with diagenetic illite; only a few sandstones have both cements. The albite mosaics, and also illite discussed below, overlie the albite and quartz cements, which formed earlier. The mosaic albite crystals vary from traces to 12 % of individual sandstones, with 3-8 % common.

The albite crystals in the mosaics are tabular to prismatic, not in optical continuity with plagioclase grains, and mostly randomly oriented (Fig. 7D). The crystals are up to 0.25 mm long and 0.01 mm wide; bigger crystals formed in larger voids. Most of the crystals are twinned, and some are doubly terminated. Most crystals are cloudy and turbid due to micro-dissolution vacuoles near and on their surfaces. In reddish-brown sandstones, the albite mosaics overlie the hematite rims on the grains. Similar hydrothermal mosaic albite in sandstones in the Hartford basin is illustrated in Heald (1956), Hubert et al. (1982), and Merino et al. (1997).

Bleached Mosaic Albite

At two locations near the center of the basin, Sugarloaf sandstones with mosaic albite cement are bleached gray-buff to light tan and are not the typical brownish-red (Figs. 1, 6). These areas are at and near 1) the Cheapside quarry in Deerfield and 2) the Route 2A locality in Greenfield, which is the large exposure behind the Super Stop and Shop market. Although hydrothermal bleaching affected the sandstones, some of the relatively impermeable mudstones remained brownish red.

At the Route 2A locality, the plagioclase grains in these bleached sandstones appear nearly uniformly "cloudy" due to pervasive vacuolization. Search of eight thin sections failed to fine authigenic illite. There are patches and isolated rhombs of ferroan dolomite. Blackened mudstone clasts in some of the fluvial channel conglomerates are surrounded by dark aureoles made of diagenetic chlorite of the high-temperature, type-2b polytype that forms at about 200°C (Fig. 7E; Hayes 1970; Lounsbury 1990; Taylor 1991).

At this outcrop, the sandstones and their mosaic albite cement are cut by 22 NE-trending normal faults, with an average orientation of N22°E, 65°NW (Fig. 8). The faults have about 0.5-1 m of normal displacement, are down to the northwest, and spaced about 10-40 cm apart. The slickenlines confirm dip-slip motion. Where exposed, the faults continue through the overlying Fall River beds and Deerfield Basalt; the Turners Falls Formation is not exposed. Twelve faults are coated by quartz druses, which overlie the slickenlines. Some of the sandstones adjacent to these mineralized faults are silicified with a few percent quartz cement.

In addition to the NE-trending normal faults, two sets of fractures average N64°W, 83°NE, and N60°E, 75°NW, forming a conjugate set (Fig. 8). Sigma-1 during compression was about 12°N84°E. These fractures lack quartz druses and do not show fault displacement. In response to opening of the Atlantic Ocean at about 180 Ma, the NW-SE extension that had been affecting the Deerfield Basin shifted to NE-SW compression (Wise 1988). The compression produced

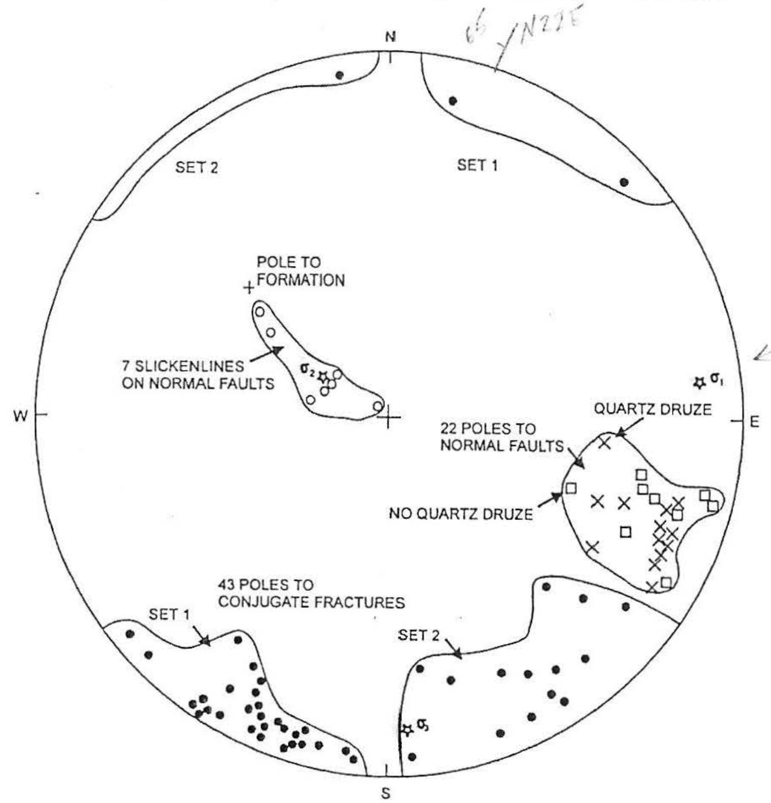

Figure 8. Poles to 22 normal faults at the Route 2A locality of the Sugarloaf Arkose in the bleached mosaic albite pattern, Greenfield, Massachusetts, plotted on the lower hemisphere of a Schmidt net. Slickenlines on the faults show dip-slip to the NW. The faults average N22°E, 65°NW. Quartz druses, younger than the slickenlines, are present on 13 of the faults. Compression formed the two sets of fractures oriented N64°W, 83°NE, and N60°E, 75°NW, forming a conjugate pair. Sigma-1 of the compression was oriented about 12°N84°E. Sigma-2 was 74°N57°W. Sigma-3 was 11°S3°E.

subhorizontal slickenlines on older normal faults and small trust faults, as well as conjugate fractures that are not paleovertical and post-date tilting of the basin strata (Fig. 8).

Goldstein (1975) first pointed out that strike-slip faults with a NE-oriented sigma-1 are common in the northern Deerfield basin. At the Cheapside quarry in Deerfield, conjugate sets of calcite veins are 1) N4°W to 45°W, dipping 60-85°SW and 2) N30°E, 60°NW (Goldstein 1975). The veins have near-horizontal slickenlines. Williams (1979) used late-stage kink bands in the metamorphic rocks of the Devonian Littleton Formation adjacent to the north end of the basin to demonstrate compression with sigma-1 oriented N55°E with a plunge of 25°NE. Wise (1988) noted that the orientation of this compression varies locally, but is real and widespread.

Illite

These sandstones have 8-24 % diagenetic illite in the grain interstices, with two morphologies: 1) plates randomly oriented or stacked in "books" along the c-axis similar to diagenetic kaolinite (Fig. 7C); and 2) delicate "hair-like," fibrous illite. Both morphologies can be present in the same pore. On X-ray diffractograms, both morphologies have sharp, narrow peaks, except for a low-angle shoulder on the 10-angstrom peak that indicates small amounts of interlayered expandable clay. The illite is the 1m polytype with diagnostic peaks at 3.68 and 2.69 angstroms.

The illite pattern is almost everywhere present in the lower 1400 m of the Sugarloaf Arkose (Figs. 1, 6). Three small patches of the illite pattern occur in the Mount Toby Conglomerate (Fig. 1). The sandstones in the illite pattern are easily weathered, forming areas of low-relief with few outcrops. On the map of Figure 1, the low areas between outcrops of Sugarloaf Arkose with the illite pattern are assumed to be also in this pattern. Fortunately, excellent outcrops are present in I-91 road cuts and along the Deerfield River in Deerfield and along the Falls River in Bernardston.

Most Sugarloaf sandstones in the illite pattern are brownish-red, but locally the hematite pigment is mostly gone and the sandstones are light tan, almost white from a distance. These bleached areas are small, varying from cms to 10s of meters. Variable amounts of hematite pigment are present on the diagenetic illite both in the unbleached and bleached areas.

Unlike the Sugarloaf arkoses in the albite-overgrowth and mosaic albite patterns, which have about 35 % feldspar in the framework grains, mostly plagioclase, and nearly ubiquitous albite overgrowths, the sandstones in the illite pattern average < 5 % feldspar and have almost no albite overgrowths. The feldspar is almost all K-feldspar, present as grains and within granite or K-feldspar-bearing gneiss fragments. Most of the K-feldspar shows various degrees of illitization along the cleavage and fractures. The few plagioclase grains are partly illitized. Illite pseudomorphs are common, apparently after the missing plagioclase (Fig. 7C). Compaction of illite pseudomorphs has blended many of them with pore-filling illite so that they are only recognizable where relict rims of hematite are present.

In many sandstones in the illite pattern, the framework grains are primarily quartz, some with etch pits on the grain surfaces or on quartz overgrowths. Concavo-convex contracts between some quartz grains reflect pressure solution, perhaps caused by increased lithostatic stress due to solution removal of framework-supporting plagioclase grains. The sandstones have 1-4 % quartz overgrowths, which predate the diagenetic illite.

Chert-illite-pyrite

An area of intensely altered, bleached gray-buff Sugarloaf sandstones with diagenetic chert, illite and pyrite covers about 3 km^3 at the northern end of the basin, about half way up in the formation (Fig. 1). This area passes transitionally into the illite pattern. Framework grains of quartz, K-feldspar, and muscovite "float" in a chert groundmass that comprises 30-40 % of the sandstones. The chert contains minor illite and pyrite. Fibrous, radiating clumps of illite fill cavities in the chert. Chert and illite fill fractures and cleavage planes in K-feldspar grains. Chalcedony spherulites and void-filling quartz coarser than chert were not observed.

In the illite-chert-pyrite pattern, grains of K-feldspar, quartz, and muscovite are present, but plagioclase grains are absent, evidently dissolved by the hydrothermal fluids. Sharply-bounded, oval areas of chert without illite are present in the illite-bearing chert groundmass; they are inferred to be pseudomorphs of plagioclase grains (Fig. 7F). Cubic and octahedral pyrite crystals about 0.01-0.2 mm in size are present

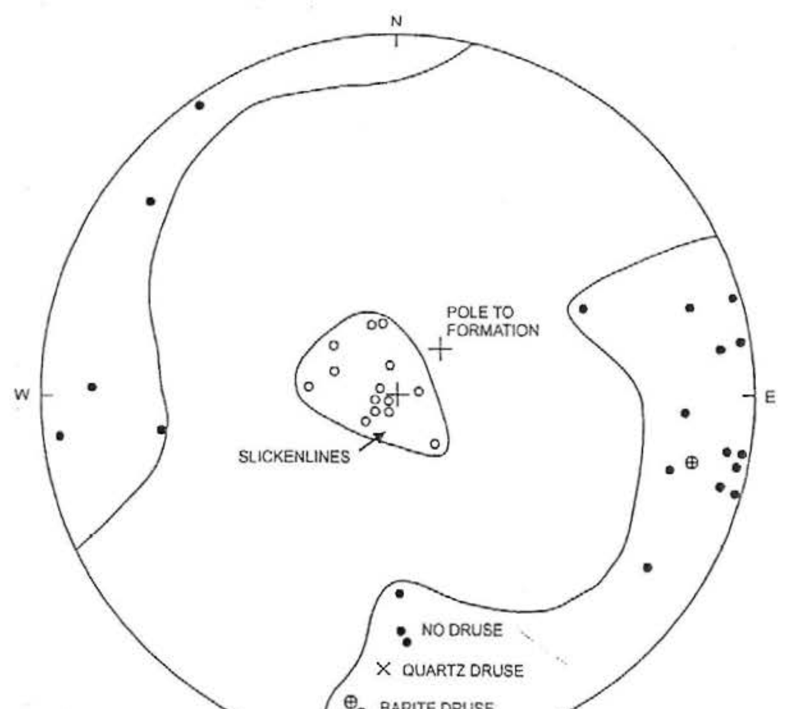

Figure 9. Poles to 25 faults and fractures at the Hoeshop Road locality of the Sugarloaf Arkose in the chert-illite-pyrite pattern, Gill, Massachusetts, plotted on the lower hemisphere of a Schmidt net. The faults and fractures average about N28°E, dipping 84°NW. Thin druses of barite or quartz coat four fractures.

in the chert groundmass and pseudomorphs. In reflected light microscopy, many of the pyrite crystals have skeletal structures due to interrupted growth and rapid cooling.

At the outcrop of the Sugarloaf Arkose in the chert-illite-pyrite pattern along Hoeshop Road in Gill, Massachusetts, 25 fractures and normal faults cut the sandstones and the chert-illite-pyrite mineralization (Figs. 1, 9). Thin druses of barite and quartz coat four of the faults. Slickenlines on the fault surfaces show dip-slip motion, down to the northwest. The sequence of formation was slickenlines, then quartz, and lastly barite with minor pyrite in the blades of barite. The average orientation of the fractures and faults is N28°E, 84°NW (Figs. 1, 8). The substantial variability in orientation of the faults suggests that the NW-SE extensional stress field shifted slightly while the faults were forming.

Calcite

At three areas in the Mount Toby Conglomerate close to the border fault, calcite and ferroan calcite fill former pores and extensively replace detrital grains and earlier albite and quartz overgrowths. The carbonate forms up to 46 % of the sandy granule conglomerates, including replacement of grains and overgrowths. Many crystals as they grew changed composition from calcite to ferroan calcite. Hematite comprises up to 10 % of the sandstones, as grain rims, hematitic mud matrix, and local pore fills. Albite and quartz overgrowths are present but uncommon. Absent are diagenetic mosaic albite, illite, or chert. Calcite-filled fractures cut every sample.

At these locations, and probably additional places along the border fault, the Mount Toby Conglomerate is shattered and lined with calcite veins, evidently due to movements on the border fault. Water moved through the fractures, filling pores with calcite/ferroan calcite and partially to completely replacing many grains. The remaining albite and quartz overgrowths peek through the younger carbonate, as through a layer of paint.

QUARTZ-CARBONATE-BARITE VEINS

Quartz-carbonate-barite (QCB) veins are present in the north-central to northern areas of the Deerfield basin, in the upper Sugarloaf Arkose, the Deerfield Basalt, and the lower and middle parts of the Turners Falls Formation. The veins mostly trend northeast, dipping steeply northwest; most are less than a few cm wide. The veins cut and are thus younger than the hydrothermally altered sandstones. The veins are similar in mineralogy, orientation, age, and origin to QCB veins in the Hartford basin described by Ryan, (1986), Gray (1988), Robinson and Woodruff (1988), Hubert et al., (1992), and Parnell and Monson (1995). In the Hartford basin, the veins are restricted to the south-central part of the basin in the vicinity of the Meriden cross-block, which was formed by a cluster of major NE-trending normal faults (Wise 1992).

In the Deerfield basin, the most abundant vein minerals are calcite and quartz, followed by ferroan calcite and then barite; very minor are siderite, metallic sulfides, and chlorite. In general, quartz dominates in the sedimentary strata and calcite in the basalt. Only a few veins are almost all barite with minor metallic sulfides, as in the Deerfield basalt 350 m southwest of the junction of Fall River and the Connecticut River where barite veins occur in and parallel to a N23°W-trending normal fault (Wise 1988). In the vicinity of Turners Falls, 80 veins in the Turners Falls Formation have an average orientation of about N50°E, 80°NW (Wise 1988). As the brine evolved, barium was added during dissolution/replacement of plagioclase grains by illite. Favoring enrichment in barium is the common presence of more barium in plagioclase than in K-feldspar, combined with the original high ratio of plagioclase to K-feldspar grains in the sands. In the Turners Falls sequence of playa redbeds and lacustrine gray/black mudstone, bitumen is present in a few veins where it precipitated last, coating earlier minerals. The only vein albite we have seen is mosaic albite in mm-wide veins and vugs in mineralized breccia in the Deerfield Basalt in the Mackin quarry in Greenfield; the veins contain mostly calcite, with some quartz and a little barite.

In the Hartford basin, the large normal faults in the Meriden cross-block opened pathways to the New Haven Arkose, tapping a hot, deep brine that had evolved deep in the basin. The brine was about 200°C, with moderate salinity (9.6-13.0 wt. % Na in fluid inclusions), rich in silica, and nearly saturated for carbon dioxide (Ryan 1986; Gray 1988). Homogenization temperatures for aqueous inclusions in quartz from the QCB veins are 110-120°C (Parnell and Monson 1995). The vein minerals were precipitated by cooling of multiple pulses of rising hot waters (Gray 1988). Formation waters also entered the veins laterally from lacustrine gray/black mudstones above the New Haven Arkose, leading to precipitation of dolomite, bitumen, and metallic sulfides at these levels, similar to the veins in Turners Falls Formation in the Deerfield basin.

BIOMARKERS

The Deerfield basin is thermally overmature for hydrocarbons, in and beyond the "gas window." Thermal maturity increases from south to north along the line of our three sample locations (Fig. 1). Three lacustrine black mudstones in the Turners Falls Formation along the Connecticut River just below the dam at Turners Falls have vitrinite reflectance values of R_o of 1.46, 1.67, and 1.73 (Table 1). Seven of the 10 lacustrine gray/black mudstones from throughout the basin listed in Table 1 had too little organic matter to measure vitrinite reflectance. The thermal alteration indices based on the color of the non-fluorescent amorphous organic material for the 10 gray/ black mudstones range from 3.2-3.6, equal to R_o values of 1.3-1.9 (Table 1).

The 1-2 wt. % total organic carbon in the 10 lacustrine gray/ black mudstones indicates that organic richness is poor to good (Table 1). However, the values of the hydrocarbon generation potential (= $S_1 + S_2$) are 0.03-0.60, indicating that producible hydrocarbons are poor because the basin is thermally overmature (Fig. 10). The plot of hydrogen and oxygen indices on a modified van Krevelen diagram indicates that the mudstones are gas prone and the organic matter evolved along the path for humic kerogen from woody or other lignin-rich material of terrestrial origin (Fig. 11). The volume of plant material washed into the lakes swamped the aquatic algae.

The map of the diagenetic patterns in the Deerfield basin shows several "hot spots" due to the upwelling of hydrothermal waters: the chert-illite-pyrite pattern; the two areas of bleached mosaic albite pattern; and small areas of the illite pattern in the Mount Toby Conglomerate (Fig. 1). Heat flow was also unevenly distributed in the Hartford basin which has local thermal anomalies indicated by biomarkers and diagenetic patterns (Pratt et al. 1988; Hubert et al. 1992; Merino et al. 1997).

$^{40}Ar/^{39}Ar$ ANALYSES OF DETRITAL MICROCLINES

The five detrital microclines from the Sugarloaf Arkose yield similar spectra with ages generally increasing from lows of about 150-170 Ma at the lowest extraction temperatures to maximum values of about 270-290 Ma (Fig. 12). Most of the apparent ages are greater than 200 Ma. Ages less than 200 Ma account for only about 5-13 % of the gas in four of the samples, whereas in sample 3 (SF-I91-A4D from the illite pattern), this low-age gas makes up about 36 % of the total released.

INTERPRETATIONS

Argon Spectra

The ages of final gas released are all older than the depositional ages of the Early Mesozoic strata. Paleocurrent maps based on crossbed data show that the source areas for the five sandstones in the Sugarloaf Arkose sampled for the microcline grains were mainly in the Pelham Dome east of the basin, perhaps extending around the northern end of the basin (Hubert and Dutcher 1999).

Robinson et al. (1998) reviewed the metamorphic history of the rocks around the Deerfield basin, concluding that west of the basin the lower to middle Paleozoic strata record metamorphism in the Taconian (455-442 Ma), Acadian (423-385 Ma), and Neo-Acadian (350-336 Ma) orogenies, whereas the Precambrian to middle Paleozoic terrane east of the basin was in addition overprinted by the Late Pennsylvanian (300-290 Ma), and Alleghanian (280-260 Ma) orogenies. The argon apparent ages of 290-270 Ma shown in Figure 12 confirm Late Paleozoic metamorphism east of the basin. In the Hartford basin, detrital muscovites in sandstones collected

S_1 = free light HC. 1st Peak < 300 °C

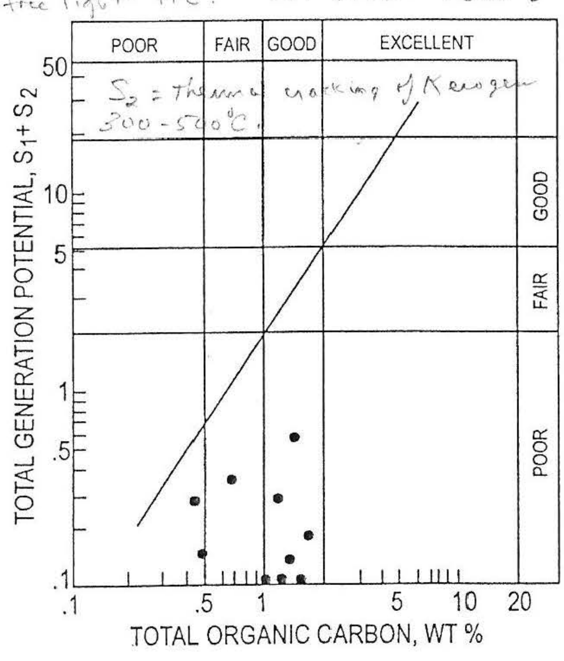

Figure 10. Plot of total organic carbon versus and hydrocarbon generation potential ($S_1 + S_2$) for10 lacustrine gray/black mudstones in the Turners Falls Formation. The mudstones have mostly "fair to good" organic richness, but poor producible hydrocarbons because the basin is thermally overmature.

definitions on p. 111

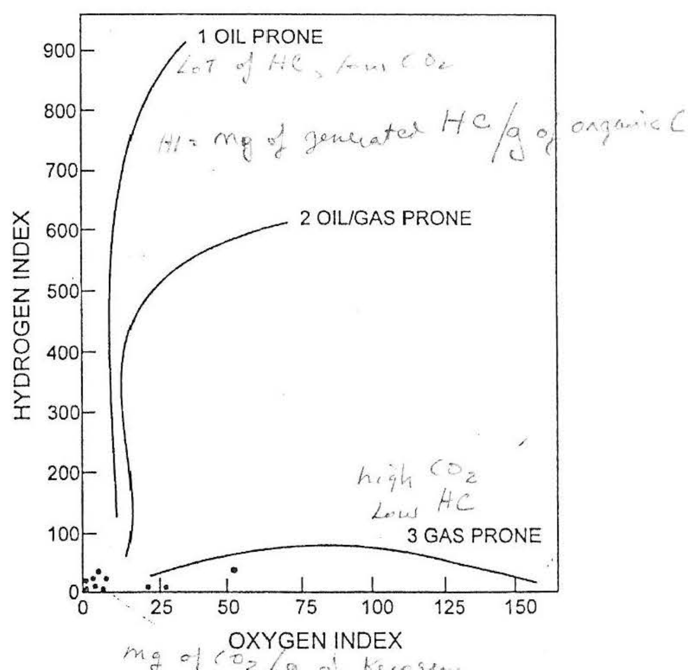

Figure 11. Modified van Krevelen diagram plotting oxygen index and hydrogen index of lacustrine gray/black mudstones in the Turners Falls Formation. The organic matter was gas prone and evolved along the path for humic kerogen from woody or other lignin-rich material, rather than aquatic algae.

 90% more oil

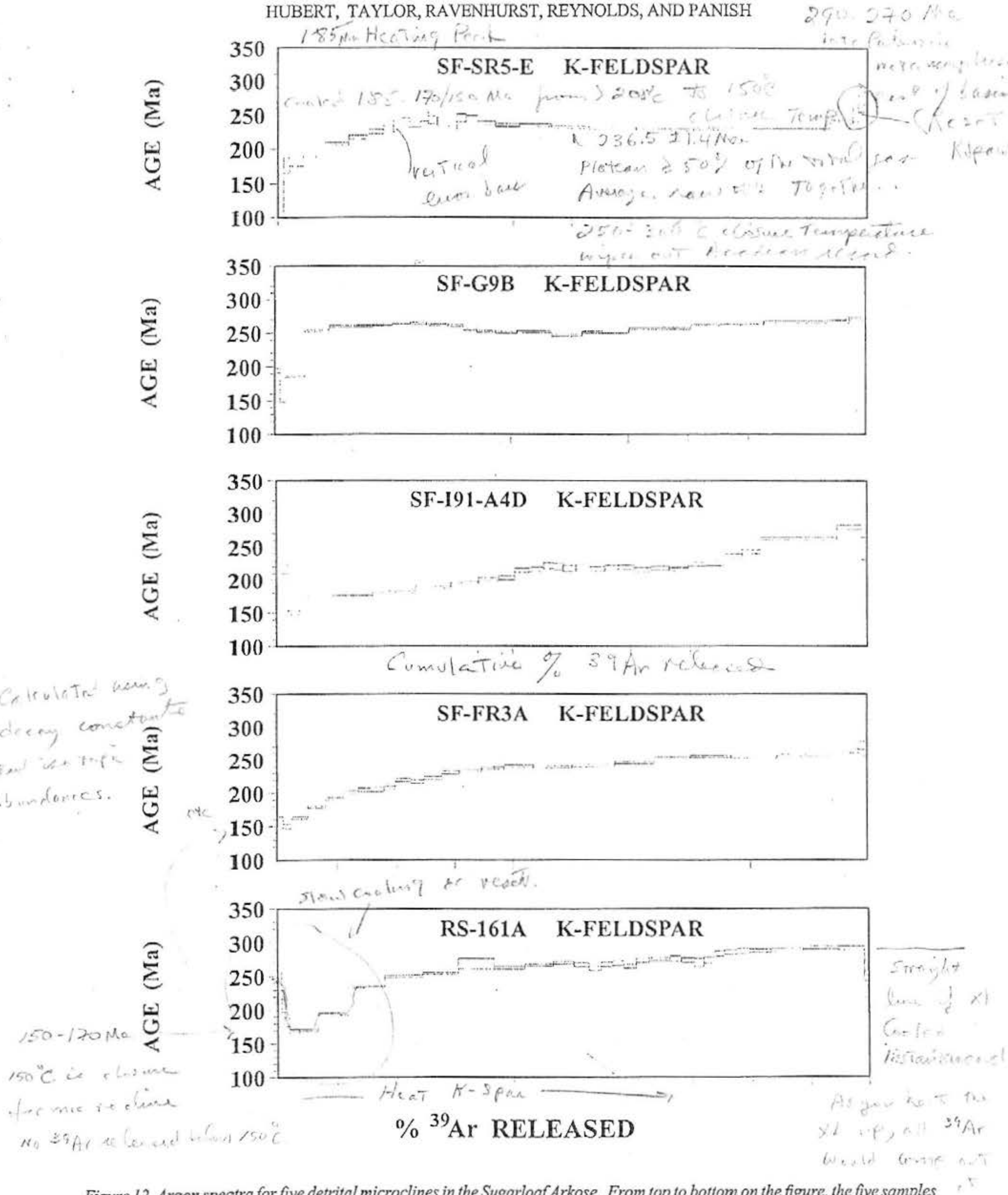

Figure 12. Argon spectra for five detrital microclines in the Sugarloaf Arkose. From top to bottom on the figure, the five samples correspond to locations 1 to 5 shown in Figure 1 and are arranged from south to north. The half-heights of open rectangles indicate the one-sigma relative uncertainties.

from the New Haven Arkose of Late Triassic age and Portland Formation of Lower Jurassic age have argon apparent ages of 300-250 Ma, also reflecting Late Paleozoic metamorphism of the source rocks east of the basin (Wintsch et al. 1997; Blevins-Walker et al. 2001). The effects of the Late Paleozoic metamorphism decrease westward, visible as deep-burial diagenesis in Lower Ordovician to Devonian strata of the Catskill Mountains and northern Appalachian basin, once deeply buried beneath overlying strata (Friedman 1987, 1990, pers. comm. 2001; Jackson et al. 1988).

Plots of inferred temperature trends versus time for the Hartford and Deerfield basins based on $^{40}Ar/^{39}Ar$ spectra for microclines and muscovites, together with zircon and apatite fission-track data, show that high heat flow under the basins associated with crustal thinning peaked at about 185 Ma (Roden and Miller 1991; Wintsch, pers. comm. 2001; Blevins-Walker et al. 2001; Boyd et al. 2001; Roden-Tice and Wintsch 2001). Figure 12 indicates that in the microclines in the Sugarloaf Arkose were at about 150°C (closure temperature of detrital microclines) at 170-150 Ma, a time after deposition ceased in the basin. The original stratigraphic fill of the Deerfield basin was about 6-7 km, comprised of 4 km preserved thickness and perhaps 2-3 km removed by erosion (Pratt et al. 1988; Olsen et al. 1992). Cooling of the Sugarloaf Arkose from well above 200°C to about 150°C from about 185 Ma to about 170-150 Ma seems reasonable considering the thickness of the basin fill and an elevated geothermal gradient of perhaps 50°C/km.

This inference of an elevated geothermal gradient in the Hartford and Deerfield basins is supported by the thinning of the crust due to regional NW-SE extension of 1-4 km relative to surrounding areas (Wenk 1989). Partial melting of the upper mantle generated basaltic magma extruded as plateau basalts via feeder dikes, including the Holyoke-Deerfield flood basalts that were fissure eruptions from the Buttress-Ware dike. Samples from the dike have $^{40}Ar/^{39}Ar$ apparent ages of 176 ± 3.8 Ma and 181 ± 6.7 Ma (Sutter and Smith 1979), compatible with an inference of cooling from a heating event that peaked at about 185 Ma.

Fission-track data for apatite in sandstones in the Deerfield basin and northern part of the Hartford basin have apparent ages that vary from 107 ± 8 Ma to 130 ± 21 Ma (Roden and Miller 1991). Apatite in crystalline rocks in the Bronson Hill anticlinorium in Massachusetts and Vermont have apparent ages of 98 ± 8 Ma to 158 ± 24 Ma (Roden 1993; Roden-Tice and Wintsch 2001). The apatites cooled through the track-annealing 70°-90°C at dates compatible with peak temperatures at about 185 Ma.

Diagenetic illite, chert, mosaic albite, chlorite and laumontite in sandstones in the Hartford basin generally record the same hydrothermal processes that affected the Deerfield basin Merino et al. (1997). The K-Ar age of diagenetic illite in sandstones in the Hartford basin is 180 ± 10 Ma (Merino et al. 1997). Locally, the 201-Ma basaltic intrusions have contact metamorphic effects where mosaic albite and chert in the sandstones adjacent to the intrusions decrease away from the basalt/sandstone contacts (Heald 1956).

Northeast-trending, mostly steeply NW-dipping, normal faults with quartz and barite druses, but no albite, cut and are younger than the hydrothermal patterns in the Deerfield basin (Figs. 8, 9). These faults formed during regional extension, before the stress field changed to compression due to ridge-push from a newly formed Atlantic Ocean.

Colors of the Strata

In the Deerfield basin, the detrital particles deposited in rivers, playas and alluvial fans were stained yellow-brown by soil-derived coatings of hydrated iron-oxides. After burial in oxidizing groundwaters, the stains spontaneously dehydrated to hematite pigment in hundreds of thousands to a few million years (Walker 1976). The hematite rims locally recrystallized to larger hematite crystals. Accompanying the process, the magnetite grains altered to hematite; ilmenite altered to hematite/rutile. In contrast, in the perennial lakes deposits, the iron-oxide stains were removed as ferrous iron-organic complexes, yielding gray sandstones and gray/black mudstones.

Hematite pigment was also generated in the sandstones of the Deerfield basin by intrastratal solution of iron-bearing accessory minerals such as biotite, hornblende, and augite (Handy 1977). This process can continue over tens of millions of years and is documented in detail for the East Berlin Formation of Early Jurassic age in the Hartford basin (Hubert and Reed 1978). Some "late" hematite was deposited by groundwater moving along joints and through permeable strata.

Locally orange-brown Liesegang rings of hydrated iron-oxides stain joints and fractures in the strata, and cover minerals in the QCB veins. These stains seem to be relatively recent, presumably from groundwater, which today issues as local small springs from the bedrock accompanied by iron-oxide staining. In the Mount Toby conglomerates at Mount Toby, calcite coats many joints and outcrop surfaces, suggesting that calcite is being precipitated from groundwater that seeps through the rocks.

Burial Cementation by Descending Groundwaters

As sediments accumulated in the Deerfield basin, albite and quartz overgrowths were the earliest cements in most sands. Driven by the hydraulic head provided by the topographic relief around eastern, northern, and western sides of the basin, groundwater moved down though the moderately compacted, unlithified sands, co-precipitating albite and quartz. Downward-moving groundwater in rift basins can penetrate at least several kilometers before rising to areas of low fluid potential (Garven and Freeze 1984).

The albite and quartz overgrowths are commonly thick and engulf the grains, indicating precipitation before severe compaction. The sandstones average about 20 % total cements, omitting sandstones with > 10 % detrital matrix. Assuming an original uncompacted porosity for the sands of about 40 % (Houseknecht 1987), porosity was destroyed about equally by compaction and cementation. This corresponds to depths of about 1.5-2 km based on compaction curves from basins around the world (Selley 1988).

Burial diagenesis in some of the lacustrine and playa sands in the Turners Falls Formation began in shallow aquifers were the groundwater was enriched in Na, Mg, Ca, and bicarbonate originally concentrated in the lakes and playas. In these sands, ferroan dolomite commonly precipitated earlier than albite and quartz. The sandstones have 20-30 % cements, implying cementation before substantial compaction.

Large volumes of water were needed to transport the sodium, silicon, and aluminum needed for the albite and quartz overgrowths. Evidently the rivers and groundwaters entering the basin were enriched with sodium leached from oligoclase-rich gneisses and schists of Lower Paleozoic age similar to the Lower Paleozoic rocks exposed today around the basin. Intrastratal solution was not a major source of sodium because detrital sodic plagioclase grains in the albite-overgrowth pattern are not partly dissolved or skeletal. Assuming a surface temperature of 20°C and a geothermal gradient in the rift valley of perhaps 45-50°C/km, and co-precipitation of albite and quartz cements at depths of 1.5-2 km, then burial cementation, and albitization of feldspars, commenced at about 90-120°C.

Deep-basinal Hydrothermal Brine

The mosaic albite, illite, chert, high-temperature chlorite, and other hydrothermal minerals were precipitated from *in situ* hot brine and upward moving plumes of hydrothermal fluids. Beginning in the earliest Jurassic at about 201Ma, the basin experienced high heat flow associated with increased rates of crustal extension and thinning of the crust. Maximum heat flow was at about 185 Ma, resulting in heating of the basin and formation of a deep-basinal brine. The brine pervasively saturated the sandstones of the Sugarloaf Arkose below the Deerfield Basalt, precipitating diagenetic illite in the hotter, deeper sandstones, and mosaic albite in the less hot, overlying sandstones. The highest temperatures were obtained in the illite-chert-pyrite pattern. As illite dissolved and/or replaced sodic plagioclase, the brine became progressively enriched in sodium and silica. Aeromagnetic survey maps of the Deerfield basin do not reveal buried basaltic bodies that could be localized sources of high heat flow (L. Brown, pers. comm. 1999, and USGS maps GP432 and GP660).

At the southern and northern ends of the basin where the Deerfield Basalt thins and pinches out, the mosaic pattern continues into the sandstones above the basalt, suggesting that the basalt was a physical and thermal barrier (Fig. 1). The barrier was not absolute because an area of mosaic albite is present above the basalt in the south-central part of the basin.

The elevated temperature of the brine favored precipitation of mosaic albite and chert rather than albite and quartz overgrowths because the higher temperatures, compared to downward-moving groundwaters, increased the rate of homogeneous nucleation (Berner 1980; Merino et al. 1997). In the Hartford basin, sandstones adjacent to some 201-Ma basaltic dikes contain mosaic albite that progressively decreases in volume away from the dikes over a distance of 20 m, demonstrating that heat played a role in generating the mosaics (Heald 1956).

The temperatures were evidently somewhat higher in the bleached mosaic albite pattern than in the brownish-red sandstones with mosaic albite. The Route 2A locality in Greenfield is a "hot spot" where hydrothermal solutions rose through the sandstones, leaving a record of high-temperature chlorite and bleaching. The sandstones are cut by younger, closely-spaced, normal faults with quartz druses, accompanied by minor silicification of the sandstones adjacent to the faults.

The Deerfield and Holyoke basalts are the same lava-flow unit, now separated by erosion (see discussion in Hubert and Dutcher 1999). At the large outcrop along Route 2 in Gill, Massachusetts, the Deerfield Basalt compared to the Holyoke Basalt is higher in sodium and lower in calcium and strontium and the average composition of the plagioclase is sodic andesine rather than labradorite (O'Toole 1981). The enrichment in sodium was perhaps due to interaction of the basalt with the basinal brine.

SUMMARY

In Late Triassic time, regional NW-SE extension due to incipient breakup of Pangaea led to sagging of the basin floor and deposition of the fluvial redbeds of the Sugarloaf Arkose. The argon spectra of detrital microclines in the Sugarloaf Arkose indicate cooling through 300-350°C at 290-270 Ma, confirming Late Paleozoic metamorphism of the Lower Paleozoic source rocks east of the basin.

As deposition proceeded, topographically-driven, "cool" groundwater passed through the sands, co-precipitating albite and quartz overgrowths, plus minor cements. In the deeper parts of the basin, feldspar grains were partly to completely albitized.

Near the Triassic-Jurassic boundary, increased rates of crustal extension and high heat flow led to melting of the upper mantle and extrusion of the Deerfield basalt lavas at about 201 Ma. Other effects of the increased rates of crustal extension were formation of the border fault, rapid subsidence of the basin floor, development of an angular unconformity on the Sugarloaf Arkose, and change from fluvial open-basin architecture of the fluvial Sugarloaf Arkose to a topographically-closed basin characterized by the playa and lacustrine strata of the Turners Falls Formation (Hubert and Dutcher 1999). The original stratigraphic fill of the Deerfield basin was perhaps about 6-7 km with deposition ending in latest Early Jurassic or early Middle Jurassic time.

Continuing crustal extension and thinning led to high heat flow that peaked about 185 Ma. The resultant elevated geothermal gradient of about 50°C/km generated a deep-basinal "hot" brine. Soaking of the sandstones in the brine and rising hydrothermal plumes superimposed the hydrothermal patterns on the earlier "cool" cements precipitated by downward-moving waters. The argon spectra for detrital microclines in the Sugarloaf Arkose indicate cooling of the sandstones through about 150°C at about 170-150 Ma.

As the NW-SE extension continued, the basin fill dropped along the border fault, tilting most of the strata towards the fault. The extensional stress formed numerous paleo-vertical to paleo-steeply inclined, NE-trending faults, along some of which rising brine deposited quartz-carbonate-barite veins.

Associated with opening of the Atlantic ocean at about 180-170 Ma, regional stress changed from extension to compression, producing in the Deerfield basin conjugate faults with local minor mineralization, and some thrust faults and folds (Wise 1988).

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