[American Journal of Science, Vol. 310, May, 2010, P. 325–363, DOI 10.2475/05.2010.01]

American Journal of Science

MAY 2010

SILURIAN-DEVONIAN AGE AND TECTONIC SETTING OF THE CONNECTICUT VALLEY-GASPÉ TROUGH IN VERMONT BASED ON U-Pb SHRIMP ANALYSES OF DETRITAL ZIRCONS

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ABSTRACT. U-Pb SHRIMP ages of detrital zircons from metasedimentary rocks of the Connecticut Valley-Gaspé trough in Vermont corroborate a Silurian-Devonian age of deposition for these strata and constrain their provenances. Ages of randomly selected detrital zircons obtained from quartzites within the Waits River and Gile Mountain Formations range from Archean to Devonian with Mesoproterozoic, Neoproterozoic, Ordovician, and Silurian age populations suggesting both eastern and western sources of the sediments. The two youngest single-grain detrital zircon ages from samples collected in the Waits River Formation are 418 ± 7 and 415 ± 2 Ma. The youngest single-grain detrital zircon age from the eastern part of the Gile Mountain Formation is 411 ± 8. The youngest detrital zircons from the western portion of the Gile Mountain Formation comprise an age population with a weighted average of 409 ± 5 Ma. These ~409 Ma zircons are likely of volcanic origin, perhaps derived from the Piscataquis magmatic belt to the east. The absence of younger volcanic zircons in the coarser-grained eastern facies of the Gile Mountain Formation suggests the eastern sediments are older and were buried during Piscataquis volcanism and deposition in the west.

The shift in protoliths from calcareous silts and muds of the Waits River Formation to quartzo-feldspathic sands of the Gile Mountain Formation implies a change from a continental slope-like depositional environment to a near-shore or terrestrial environment of deposition. This change supports a transition in the nature of the basin from an intercontinental back-arc extensional setting to a foreland basin setting. Maximum depositional ages of sediments above and below this facies boundary constrain the timing of transition in basin style between about 415 and 411 Ma. Given the timing of the approaching Acadian wedge, this shift in basin style likely reflects westward migration of thrust sheets during the Acadian orogeny. The fine-grained nature of the youngest silts, muds and turbidites suggests that sedimentation occurred in increasingly deeper water. The implied basin subsidence was likely caused by lithospheric flexure as the Acadian wedge approached from the east. The timing of this subsidence is constrained to be younger than the youngest zircons at about 409 Ma.

Key words: Detrital zircon, Geochronology, Connecticut Valley-Gaspé trough, Waits River Formation, Gile Mountain Formation.

INTRODUCTION

Silurian basins developed on Laurentian and peri-Gondwanan basement have been identified along the length of the Appalachians from northern Québec (for example, Bourque and others, 1995, 2000; Rankin and others, 2007) to South Carolina

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(for example, Dennis, 2007). One such basin, the Connecticut Valley-Gaspé trough (CVGT) of the northern Appalachians, stretches from southern Connecticut to Gaspé Bay in Québec (Tremblay and Pinet, 2005; Hibbard and others, 2006). Despite widespread exposures and numerous studies focusing on this basin, controversies still exist regarding formation of the CVGT as well as the age and stratigraphy of the rocks within. Proposed origins include: 1) intercontinental extensional setting driven by slab detachment and lithospheric delamination causing asthenospheric upwelling (van Staal and de Roo, 1995; Robinson and others, 1998; Tremblay and Pinet, 2005; Rankin and others, 2007), 2) a back-arc basin above a west-dipping subduction zone (Karabinos and others, 1998, 2008), 3) orogen-normal extension produced by rapid subduction zone rollback (Moench and Aleinikoff, 2003), 4) a transpressive environment that developed a pull-apart basin (Keppie and Dostal, 1994), or 5) proximal sedimentation derived from the approaching Acadian wedge making the CVGT a foreland basin (Bradley and others, 2000).

This study seeks to contribute to our understanding of the tectonic setting of the CVGT in New England by investigating the age and provenance of the metasedimentary rocks in eastern Vermont using U-Pb ages of detrital zircons. This strategy utilizes the age distributions of detrital zircons to identify likely sources for sediments of the CVGT, and thus determines which terranes had sufficient relief to shed sediments into the basin. Our approach represents the first detrital zircon study in the CVGT. These data are used to refine previous stratigraphic studies in Vermont which have been frustrated by the lack of constraints on the age of deposition of sediments in the CVGT and which have typically inferred a broadly Silurian-Devonian age (for example, Doll and others, 1961; Hatch and others, 1988; Lyons and others, 1997). The youngest ages of detrital zircon populations identified in this study constrain the maximum depositional age of these sediments, allowing stratigraphic correlation with documented tectonic events. We apply these results to help reconstruct the tectonic history of this >1000 km long Silurian-Devonian basin.

GEOLOGIC SETTING

The Connecticut Valley-Gaspé trough is one of many regionally extensive packages of stratified rocks identified across strike in New England (fig. 1). In Vermont, the CVGT is located between remnants of two early Paleozoic volcanic arcs—the Shelburne Falls arc to the west (Karabinos and others, 1998; Karabinos and Hepburn, 2001) and the Bronson Hill arc to the east (Stanley and Ratcliffe, 1985; Tucker and Robinson, 1990; Moench and Aleinikoff, 2003). In New Hampshire, Maine, and New Brunswick, the CVGT is interpreted to merge with the Central Maine trough (CMT, fig. 1) (Osberg and others, 1989; Tremblay and Pinet, 2005; Hibbard and others, 2006; Rankin and others, 2007). Silurian deposition of sediments in the CVGT and CMT basins effectively buried the Ordovician Iapetan suture along the "Red Indian line" (for example, Williams and others, 1988), obscuring the boundary between Laurentian crust to the west and Ganderian crust to the east (van Staal and others, 1998; Rankin and others, 2007; Aleinikoff and others, 2007).

The Silurian to Devonian metasedimentary rocks of the Connecticut Valley-Gaspé trough (CVGT) underlie a large part of eastern and northeastern Vermont (for example, Doll and others, 1961; fig. 2A) and extend as an outlier into western New Hampshire (Lyons and others, 1997). The majority of the rocks occur in the Waits River and Gile Mountain Formations, which consist of interbedded variably calcareous and carbonaceous phyllite and schist, quartzite, and impure siliceous marble (for example, Doll and others, 1961; Lyons and others, 1997). Distribution of these rock types (fig. 2A) is based largely on the mapping of lithofacies (Ern, 1963; Chang and others, 1965; Hepburn and others, 1984; Walsh and Ratcliffe, 1994; Walsh and others, 1994, 1996a, 1996b; Armstrong, 1994, 1997; Armstrong and others, 1997; Walsh, 1998;

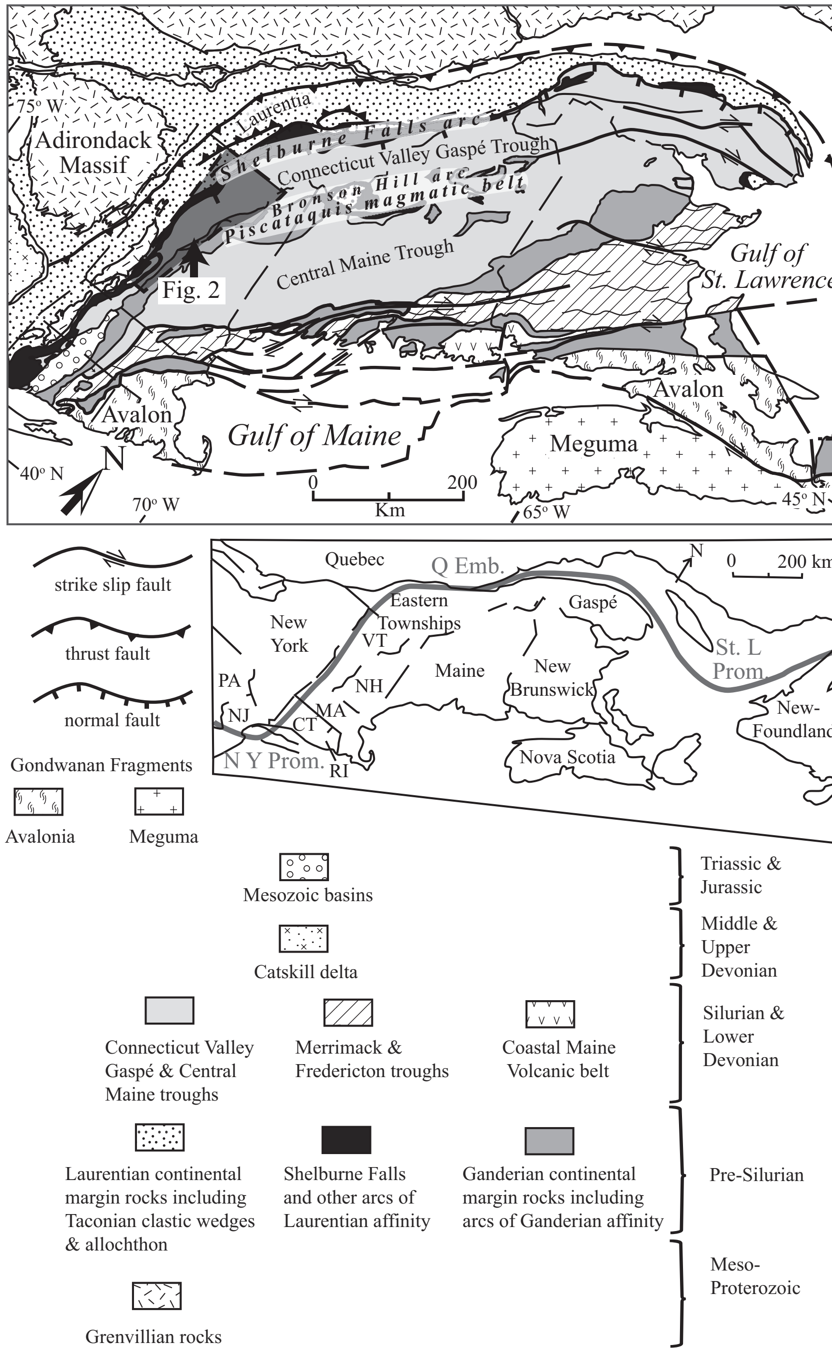

Fig. 1. Generalized tectonic map of the northern Appalachians showing the Connecticut Valley-Gaspé and Central Maine troughs, the Shelburne Falls and Bronson Hill arcs, the Piscataquis magmatic belt, the Avalon and Meguma terranes and Laurentia. Inset map shows the St. Lawrence Promontory (St. L Prom.), Québec embayment (Q Emb.), and the New York Promontory (N Y Prom.) along the western boundary of Laurentia (bold gray line). Location of figure 2 is also shown (shaded box). Modified from Rankin and others (2007).

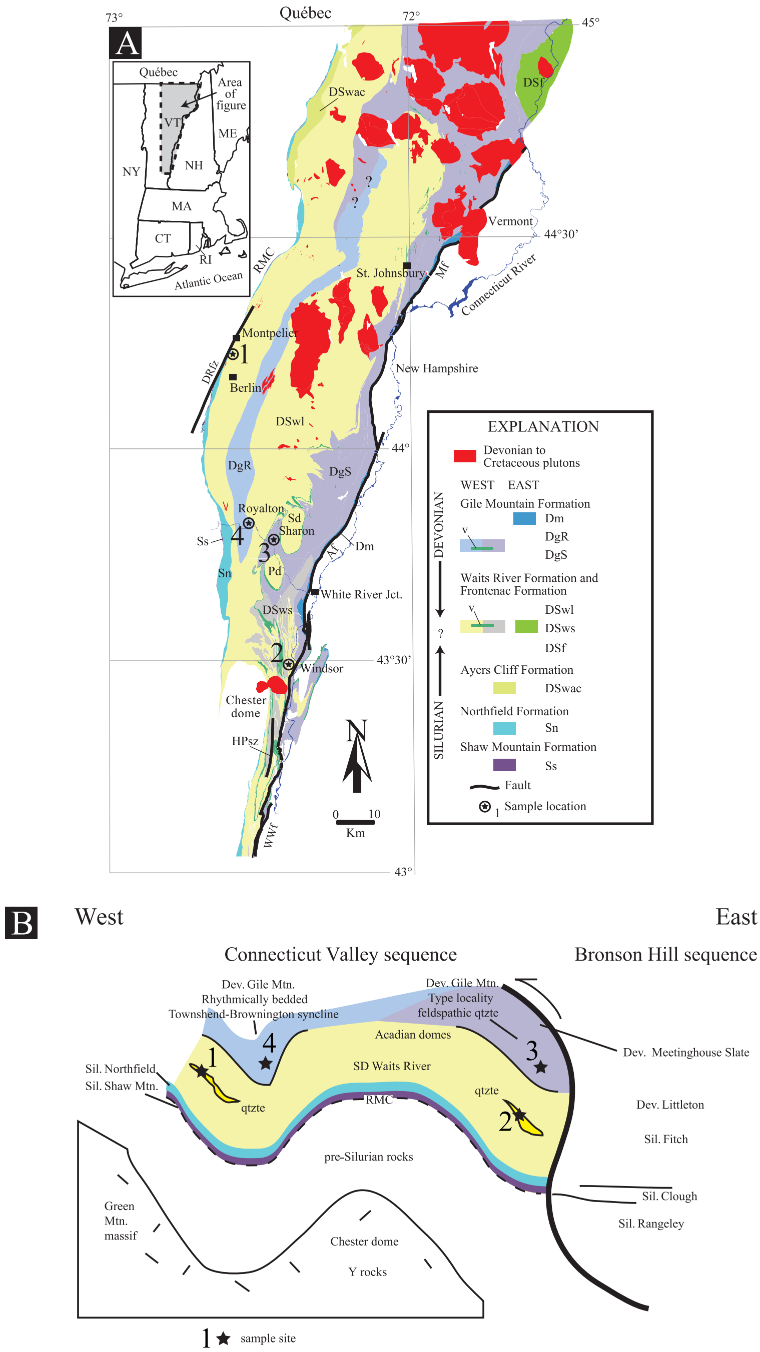
A
73°
Québec
72°
45°
Québec
Area of figure
VT
ME
NY
NH
MA
CT
RI
Atlantic Ocean
DSwac
DSf
?
?
Vermont
44°30'
RMC
St. Johnsbury
Mf
Connecticut River
Montpelier
1
DRfz
Berlin
New Hampshire
DSwl
44°
DgR
DgS
Royalton
Sd
Sharon
Ss
4
3
Sn
Pd
AF
Dm
White River Jct.
DSws
2
Windsor
43°30'
Chester dome
HPsz
N
0
10
Km
WWf
43°
EXPLANATION
Devonian to Cretaceous plutons
WEST EAST
DEVONIAN
Gile Mountain Formation
Dm
v
DgR
DgS
Waits River Formation and Frontenac Formation
v
DSwl
DSws
DSf
?
Ayers Cliff Formation
DSwac
SILURIAN
Northfield Formation
Sn
Shaw Mountain Formation
Ss
Fault
1 Sample location
B
West
East
Connecticut Valley sequence
Bronson Hill sequence
Dev. Gile Mtn.
Rhythmically bedded
Townshend-Brownington syncline
Dev. Gile Mtn.
Type locality
feldspathic qtzte
4
3
Acadian domes
Dev. Meetinghouse Slate
Sil. Northfield
Sil. Shaw Mtn.
1
SD Waits River
qtzte
qtzte
RMC
Dev. Littleton
2
Sil. Fitch
pre-Silurian rocks
Sil. Clough
Sil. Rangeley
Green Mtn. massif
Chester dome
Y rocks
1 sample site

Fig. 2.

Ratcliffe, 2000a, 2000b; Ratcliffe and Armstrong, 2001; Walsh and others, 2010) and application of the regional facies model of Hatch (1988a). Generally, the Waits River Formation is dominated by interbedded metapelite and impure siliceous marble, but locally contains interbedded quartzite. The Gile Mountain Formation is dominated by metapelite and interbedded quartzite, and is only locally calcareous.

The CVGT has been subdivided into a western part, variably and informally named the Connecticut Valley (or Vermont) sequence or trough, and a generally correlative eastern part, the Silurian-Devonian part of the Bronson Hill sequence (Hatch, 1988b; Armstrong and others, 1997; Thompson and others, 1997; Rankin and others, 2007). Here we follow the informal usage of Rankin and others (2007), and refer to the rocks in Vermont as the "Connecticut Valley sequence" (CVS) (fig. 2A).

In Vermont, pre-Silurian metamorphic rocks underlie the CVS to the west. The contact is informally named the "Richardson Memorial contact" (RMC, fig. 2A), historically interpreted as either a Silurian unconformity (Cady, 1956; Doll and others, 1961; Hatch, 1982), a fault related to Acadian (Devonian) deformation (Westerman, 1987; Hatch, 1988b), or a syn-depositional fault and unconformity (Karabinos, 1998). The eastern side of the CVS is locally an Acadian fault, an Alleghanian fault, or a Mesozoic fault along the contact with rocks of the Bronson Hill anticlinorium (fig. 2B; Hatch, 1988b; Robinson and others, 1988; Moench and others, 1995; Rankin, 1996a, 1996b; Armstrong and others, 1997; Lyons and others, 1997; Hannula and others, 1999; Spear and others, 2002, 2008; Rankin and others, 2007). Alternatively, others consider the eastern contact to be an unconformity (Thompson and others, 1990, 1997; Trzcienski and others, 1992). The eastern contact is particularly problematic east of Windsor, Vermont (fig. 2A) where it has been shown as either the Monroe fault (Lyons and others, 1997) or as an unconformity (Thompson and others, 1990, 1997).

In Vermont, metasedimentary rocks of the Connecticut Valley sequence (CVS) include the Shaw Mountain, Northfield, Waits River, and Gile Mountain Formations, and the Meetinghouse Slate Member of the Gile Mountain Formation (figs. 2 and 3). Discontinuous layers of metavolcanic rock occur within the Waits River and Gile Mountain Formations (for example, Doll and others, 1961; Armstrong and others, 1997; fig. 3). Geochemical signatures of these metavolcanic rocks in the Standing Pond Volcanic Member of the Waits River Formation suggest they may record a widespread rifting event during the deposition of some CVS sediments (Hepburn, 1991; Slack, 1994; Karabinos, 1998; Karabinos and others, 1998; Slack and others, 2001). In far northeastern Vermont and northwestern New Hampshire, outside our study area, the CVGT includes metasedimentary and metavolcanic rocks of the Frontenac Formation that occur stratigraphically beneath the Devonian part of the trough and range in age

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Fig. 2. (A) Regional geologic map of the Connecticut Valley sequence (CVS) in northeastern Vermont based largely on mapping of lithofacies and application of the regional facies model of Hatch (1988a). Abbreviations: v—metavolcanic rocks; Mf—Monroe fault, Af—Ammonoosuc fault, HPsz—Hartness Park shear zone, WWf—Westminster West fault, DRfz—Dog River fault zone, RMC—Richardson Memorial contact, Pd—Pomfret dome, Sd—Strafford dome. Gile Mountain Formation facies: Dm—Meetinghouse Slate Member (QM)—Thinly bedded metapelite, DgR—Royalton facies (RQM)—Turbiditic rhythmically bedded quartzite and metapelite, DgS—Sharon facies (Q)—Thickly bedded quartzite and metapelite. Designations Q, QM, and RQM in the Gile Mountain Formation show the correlative units of Hatch (1988a). Waits River and Frontenac Formation facies: DSwl—Interbedded metapelite, impure metalimestone, and minor quartzite, DSws—Interbedded metapelite and minor impure metalimestone and quartzite, DSf—metasedimentary and metavolcanic rocks. Ayers Cliff Formation facies: DSwac—Impure metalimestone. Northfield Formation facies: Sn—Metapelite. Shaw Mountain Formation facies: Ss—Conglomerate. Compiled from Walsh and Ratcliffe, 1994; Walsh and others, 1994, 1996a, 1996b; Armstrong, 1994, 1997; Armstrong and others, 1997; Lyons and others, 1997; Walsh, 1998; Ratcliffe, 2000a, 2000b; Ratcliffe and Armstrong, 2001; Walsh and others, 2010. (B) Schematic cross section including rocks of the CVS and underlying pre-Silurian rocks including Proterozoic rocks of the Green Mountain massif and the Chester dome. Generally correlative Bronson Hill sequence to the east is shown thrust over the CVS. Sample sites are shown with stars.

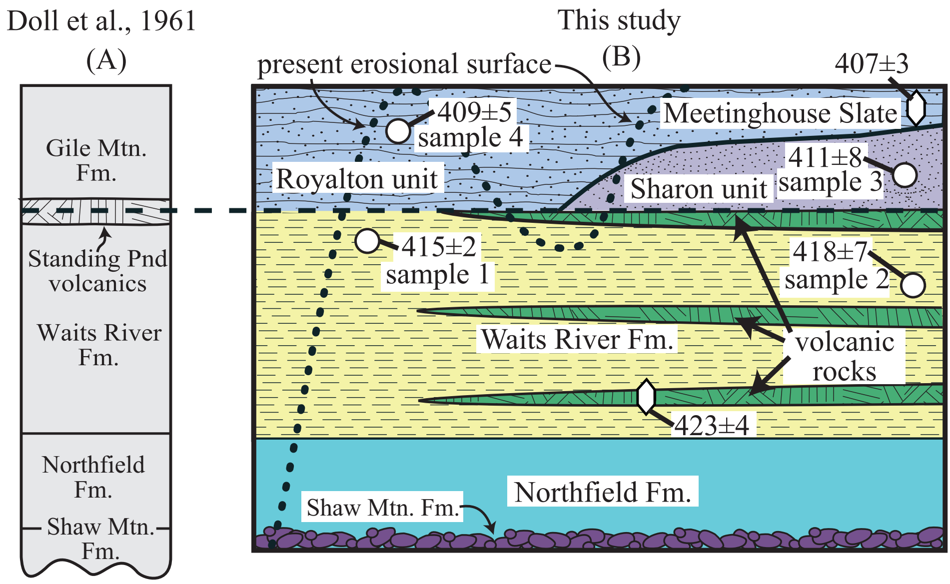


Fig. 3. Two stratigraphic models for the Connecticut Valley sequence (CVS). (A) Stratigraphic column from Doll and others (1961) showing the basal Shaw Mountain Formation and the Northfield Formation underlying the Waits River Formation. The Gile Mountain-Waits River boundary was marked by the Standing Pond Volcanic Member of the Waits River in their cross-sections, but shown as a discontinuous unit along a lateral facies boundary in their correlation of map units. (B) Our stratigraphic model for the CVS showing maximum depositional ages at each sample site obtained from the youngest detrital zircon in each sample (circles) and the age of volcanic horizons (diamonds, 423 ± 4 from Aleinikoff and Karabinos, 1990; 407 ± 3 from Rankin and Tucker, 2009). Multiple discontinuous interbedded volcanic units are shown schematically after Armstrong and others (1997). The Gile Mountain Formation is informally divided into the eastern Sharon facies and the western Royalton facies, which may be correlative with the Meetinghouse Slate and the Littleton Formation. The present erosional surface is shown (dotted black line) identifying surface exposure from west to east in central Vermont.

from Silurian (Moench and others, 1995) to Early Devonian (Lavoie and Asselin, 2004). Rocks of the Frontenac Formation are probably correlative with the Waits River Formation (for example, Lyons and others, 1997; Lavoie and Asselin, 2004). The correlative Silurian-Devonian rocks of the Bronson Hill sequence, in western and central New Hampshire, include metasedimentary and metavolcanic rocks of the Clough, Fitch and Littleton Formations (for example, Billings, 1937; Elbert and others, 1988). The Clough Formation, comprised of quartzite and a basal conglomerate (for example, Elbert and others, 1988), may correlate with the Shaw Mountain Formation, whereas graded beds of the Littleton Formation may correlate with parts of the Gile Mountain Formation (for example, Rankin and others, 2007).

The CVS rocks experienced at least three periods of folding (Woodland, 1977; Fisher and Karabinos, 1980; Walsh and others, 1996a; Walsh, 1998; Ratcliffe, 2000a, 2000b) and metamorphism from greenschist to amphibolite facies conditions mainly during the Devonian Acadian orogeny (Laird and others; 1984; Sutter and others, 1985; Harrison and others, 1989; Spear and Harrison, 1989). The metamorphic rocks are cut by Devonian and Cretaceous, largely granitoid, plutonic rocks (Doll and others, 1961; fig. 2A).

The age of metasedimentary rocks of the CVS in Vermont is based on limited fossil and isotopic evidence and regional correlations. Regionally in New England the depositional age of sediments in the CVS is considered to be Silurian to Devonian (Doll and others, 1961; Boucot and Drapeau, 1968; Hatch, 1988a; Lyons and others, 1997). In the less-deformed and lower grade rocks of the Gaspé Belt to the north, fossil control is much better and biostratigraphic data support a Late Silurian (Pridoli) to Early Devonian (Emsian) age range for the rocks above the Salinic unconformity of Boucout (1962) in southern Québec (Hueber and others, 1990; Lavoie and Asselin, 2004). Still farther north in the Gaspé Belt of Québec and New Brunswick, rocks above the Salinic unconformity are as old as the Early Silurian (late Llandoverian) (Bourque and others, 1995, 2000; Malo, 2001; Wilson and others, 2004). However, structural complications and a lack of modern detailed mapping in northern Vermont limit definitive correlations and interpretations of the stratigraphic sequence in the CVS. Argillaceous units on the west and east sides of the CVS include the Northfield Formation and Meetinghouse Slate Member of the Gile Mountain Formation, respectively (fig. 2A). The age and stratigraphic position of the Northfield Formation remains unresolved. The Northfield Formation has been interpreted as occurring both below (Doll and others, 1961) and above (Westerman, 1987; Hatch, 1988a) the Waits River Formation. The Meetinghouse Slate has also been interpreted as both older (Doll and others, 1961; Rankin and others, 2007) and younger (Hatch, 1988a; Lyons and others, 1997) than other rocks included in the Gile Mountain Formation. In yet another complication, the Meetinghouse has been correlated with the Northfield Formation either below the Waits River Formation (Thompson and others, 1997) or above it (Hatch, 1988a). A new U-Pb zircon TIMS age of 407 ± 3 Ma from a metarhyolite in the Meetinghouse Slate by Rankin and Tucker (2009) places the Meetinghouse near the top of the Gile Mountain Formation and supports interpretations by Hatch (1988a) and Lyons and others (1997). We place the Northfield below the Waits River in accordance with Doll and others (1961), but acknowledge the remaining uncertainty regarding the stratigraphic position of the Northfield Formation.

On the west side of the CVS above the basal unconformity, Middle Silurian to Early Devonian fossils in the Shaw Mountain Formation provide some control on the age of the rocks (Boucot and Thompson, 1963; Boucot and Drapeau, 1968; Doll, 1984) historically interpreted as the base of the section (Doll and others, 1961). According to Boucot and Drapeau (1968, p. 19) "the Shaw Mountain Formation has yielded fossils that can be of Ludlow and Pridoli age, although they could be as old as Upper Llandovery (C_3 or younger) or as young as Lower Gedinnian." The possibility of either a major fault (Westerman, 1987; Hatch 1988a) or a transgressive disconformity (Ratcliffe and Aleinikoff, 2000) along the base of the CVS at its western limit complicates the regional significance of the age of the Shaw Mountain. Early Devonian Emsian (Hueber and others, 1990) to Lochkovian (Lavoie and Asselin, 2004) fossils from the Compton Formation in Québec, the possible northern correlative of the Gile Mountain Formation, provide age control for the upper part of the CVS. The age of the Waits River Formation is less well-constrained. Cady (1950) reported the occurrence of cup corals from several localities within the Waits River Formation and suggested a Middle Ordovician age for them. However, Cady (1956) inferred a Silurian age for the Waits River Formation based on regional correlation with fossiliferous rocks subsequently reported by Boucot and others (1958) in southern Vermont and Massachusetts. Hatch (1988a) and Hueber and others (1990) re-evaluated the rocks studied by Cady and reported that they did not appear to contain definitive fossils. Several other studies reported the presence of plant fossil, crinoid and echinoderm fragments within the Waits River Formation but none provided specific age constraints (Berry, 1985; Bothner and Finney, 1986; Finney, 1986; Hueber and others, 1990).

The classical interpretation by Doll and others (1961) separated the major metasedimentary units of the CVGT, the Waits River and Gile Mountain Formations, based on the interpretation that a major belt of volcanic rocks, the Standing Pond

Volcanic Member of the Waits River Formation, occupied a chronostratigraphic position between the two formations. The assignment of rocks to the Gile Mountain Formation was based on the assumption that rocks mapped as the Standing Pond Volcanic Member separate older rocks with abundant limestone (Waits River) from younger rocks with little or no limestone (Gile Mountain). Modern quadrangle-scale (1:24,000) mapping (Walsh and others, 1996a; Armstrong and others, 1997; Walsh, 1998) indicates that limestones occur in roughly equal abundance stratigraphically below and above the thick belts of volcanic rocks and that more than one horizon of volcanic rocks is present in places. Thus it is not always possible to separate two distinct formations based on the abundance of volcanic- and limestone-bearing rocks. In the Hanover, New Hampshire area, Lyons (1955) also noted that the Waits River and Gile Mountain Formations could not be separated on a lithologic basis because the Gile Mountain became more calcareous and the Waits River became more arenaceous from north to south. To date, only one age has been determined from the belt of volcanic rocks. Aleinikoff and Karabinos (1990) and Hueber and others (1990) reported a U-Pb zircon TIMS age of 423 ± 4 Ma from a felsic rock from the Waits River Formation in Springfield, Vermont. The sample was collected from a 50-cm-thick, pale-gray, fine-grained epidote-chlorite-albite-quartz granofels layer within a coarser-grained sequence of phenocrystic feldspathic schist, granofels, and greenstone. Aleinikoff and Karabinos (1990) interpreted the layer as a dike but left open the possibility that it was a volcanic layer. Walsh and others (1996a) and Armstrong and others (1997) interpreted the layer as a bed because of the lack of unequivocal cross-cutting relationships and the presence of many similar, yet thinner, layers within a largely felsic volcaniclastic map unit. The Silurian date provides either the age of deposition of the felsic unit, and therefore the age of the Waits River Formation there, or a minimum age for the deposition of sediments at that locality. Thus, precise ages of deposition for much of this stratigraphic sequence are lacking. This study was designed in part to help resolve this age uncertainty using the ages of detrital zircons.

METHODS

Sampling Strategy

A sampling strategy capable of characterizing the tectonic setting during the depositional history of sediments in the CVS must target rocks having both spatial and temporal variations. Sampling sites were therefore chosen within both the presumed older Waits River Formation and the younger Gile Mountain Formation.

The Gile Mountain and Waits River Formations are separated into major lithofacies based on reconnaissance and recent 1:24,000-scale mapping. In the Gile Mountain Formation a feldspathic quartz-rich facies with interbedded argillite was identified in the eastern part of the CVGT (Hatch, 1988a). Rhythmically-bedded quartzite interpreted as a turbidite facies in the western part of the basin (Fisher and Karabinos, 1980) led Hatch (1988a) to suggest that this facies represents a transition from an eastern proximal facies to a more distal facies in the west (Hatch, 1988a). Because of this facies transition, we collected samples of the Gile Mountain from both the eastern and western locations in the CVS (fig. 2) in order to test the eastern source hypothesis and establish the tectonic setting of the basin throughout its development. Similarly, we sampled rocks mapped as Waits River Formation from both the western and eastern parts of the CVS (fig. 2). Both samples of Waits River Formation come from lithologically similar rocks.

Analytical Procedures

Approximately 10 kg of quartzite were collected at each of four sampling sites; two in the Waits River Formation and two in the Gile Mountain Formation. Samples were passed through a jaw crusher and disc grinder to produce sand to silt-sized particles. Zircons were concentrated using a Wilfley table, a Frantz magnetic separator and heavy liquids followed by hand picking when necessary. Euhedral, doubly-terminated zircons were hand picked from one sample (sample 4) using a binocular microscope. To limit sample bias, separates of >2000 grains from each sample were poured onto double-sided tape. In addition, ~50 hand-picked euhedral grains from sample 4 were placed adjacent to the poured grains. The >8000 zircons were mounted in epoxy, ground approximately to half-thickness, and polished sequentially using 6 μm and 1 μm diamond suspensions. Images of all zircons were obtained in reflected and transmitted light to identify cracks, mineral inclusions and fluid inclusions. Cathodoluminescence (CL) imagery of zircons performed on a scanning electron microscope (SEM) was used to identify growth zoning within individual grains.

Of the >2000 detrital zircons imaged from each sample, 60 were randomly chosen for U-Pb geochronology. In addition to analyzing the anhedral rounded grains, sixteen handpicked, euhedral, doubly-terminated zircons from sample 4 were analyzed on their tips. Zircons were analyzed on the U.S. Geological Survey/Stanford University sensitive high resolution ion microprobe-reverse geometry (SHRIMP-RG) instrument in Stanford, California following the methods of Williams (1998). A primary oxygen beam with a current between 5 and 6 nA and a spot size of 15 to 25 μm was used to ablate a pit ~1 μm deep within individual growth zones. A single analysis consists of four cycles through the mass stations for unknowns and five cycles for standards. Zircon standards used included R33 (419 ± 1 Ma; Black and others, 2004) for calibration of $^{206}Pb/^{238}U$ and CZ3 for calibration of U concentrations, estimated to be ± 20 percent. Data reduction was performed using Squid 1 (Ludwig, 2001) and data were plotted using Isoplot 3 (Ludwig, 2003). The degree of discordance of U-Pb data was assessed using standard concordia diagrams. Relative probability plots of age distributions included analyses of detrital zircons that were less than 15 percent discordant (table 1). For zircon ages younger than ~1200 Ma we use the $^{206}Pb/^{238}U$ age; the $^{207}Pb/^{206}Pb$ age is used for zircons older than ~1200 Ma. U-Pb data for hand picked grains from one sample are plotted on a Tera-Wasserburg concordia plot to visually identify a coherent age group. A weighted average of individual $^{206}Pb/^{238}U$ ages was calculated to obtain an age for this population. One-sigma errors are reported for all analyses. In this study, we follow the geologic time scale of Gradstein and others (2004).

RESULTS

Most of the >2000 zircons show oscillatory and sector zoning typical of igneous zircons, and some show metamorphic rims. In all cases, randomly selected zircon cores were analyzed. Particular care was used to avoid fractured zircons and obvious metamorphic overgrowths. Sixty grains per sample were analyzed according to guidelines in Dodson and others (1988). Detrital zircon ages obtained from the four samples analyzed in this study fall into three broadly defined age populations: 1) ~405 to 755 Ma, 2) ~915 to 2150 Ma, and 3) >2.5 Ga (figs. 4 and 5; table 1).

Waits River Formation

Sample 1, from the Waits River Formation, was collected from a mapped 2-m-thick light-gray quartzite layer interbedded with considerably more abundant gray phyllite and siliceous marble (Walsh and others, 2010) in the western part of the CVS south of Montpelier along I-89 (DSwl, fig. 2). This sample contains numerous subrounded to rounded zircons 20 to 60 μm in diameter. CL imaging reveals oscillatory and sector zoning in individual grains (fig. 6A). Oscillatory-zoned cores are commonly truncated by mantle and rim overgrowths, with all zones truncated at grain boundaries thus clearly indicating that these are detrital zircons.

TABLE 1

SHRIMP U-Th-Pb data for detrital zircons from metasedimentary rocks of the CVS

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ [1,2] (Ma)	err[3] (Ma)	$^{207}Pb/^{206}Pb$ [1,5] (Ma)	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$ [4]	err[3] (%)	$^{207}Pb/^{206}Pb$ [4]	err[3] (%)
Waits River Formation Sample 1 (I-89 southbound, UTM Zone 18 0692832E, 4899528N, NAD83 datum)														
61206-1-1	-0.000014	0.0557	0.02	1050	0.51	432.3	2.3				14.41	0.5	0.0559	1.2
61206-1-2.1	-0.000017	0.0955	-0.20	215	0.38	1572.5	16.2	1543	19	-2	3.63	1.1	0.0957	1.0
61206-1-3.1	-0.000020	0.0595	0.13	595	0.98	548.5	3.7				11.24	0.7	0.0598	1.3
61206-1-4.1	-0.000048	0.0730	-0.01	125	0.27	1014.5	14.2	1032	38	2	5.86	1.4	0.0736	1.9
61206-1-5.1	0.000303	0.0770	-1.43	116	0.49	*1409.8*	*20.7*	1007	79	-40	4.17	1.5	0.0727	3.9
61206-1-6.1	-0.000020	0.0767	-0.16	284	0.37	1148.1	10.6	1121	24	-2	5.14	1.0	0.0770	1.2
61206-1-7.1	-0.000016	0.1365	0.58	168	0.44	2115.6	25.5	2186	14	3	2.56	1.2	0.1367	0.8
61206-1-8.1	-0.000458	0.0746	0.31	14	0.32	*984.1*	*42.3*	1222	105	19	6.00	4.4	0.0810	5.3
61206-1-9.1	0.000005	0.0796	0.03	223	0.11	1180.6	12.2	1186	29	0	4.97	1.1	0.0796	1.5
61206-1-10.1	0.000019	0.0984	-0.33	286	0.51	1647.5	15.6	1589	23	-4	3.45	1.0	0.0981	1.3
61206-1-11.1	0.000055	0.1838	0.57	100	1.08	2641.0	45.3	2681	14	1	1.97	1.5	0.1831	0.9
61206-1-12.1	0.000025	0.0939	0.20	1368	0.48	1471.4	5.4	1500	11	2	3.89	0.4	0.0936	0.6
61206-1-13.1	0.000001	0.0939	0.28	764	0.64	1457.6	7.9	1507	10	3	3.93	0.6	0.0939	0.5
61206-1-14.1	-0.000003	0.1161	0.54	888	1.52	1822.4	9.0	1898	7	4	3.04	0.5	0.1162	0.4
61206-1-15.1	-0.000026	0.0868	0.05	168	1.06	1346.3	15.5	1363	25	1	4.30	1.2	0.0871	1.3
61206-1-16.1	-0.000007	0.1046	0.33	485	0.77	1656.2	11.0	1709	11	3	3.40	0.7	0.1047	0.6
61206-1-17.1	-0.000012	0.0574	0.18	984	0.81	449.6	2.3				13.82	0.5	0.0575	1.1
61206-1-18.1	-0.000073	0.0719	0.25	84	0.50	922.8	14.9	1012	48	9	6.47	1.7	0.0729	2.3
61206-1-19.1	0.000003	0.1149	0.72	207	0.25	1776.4	18.1	1878	15	5	3.13	1.0	0.1149	0.8
61206-1-20.1	0.000022	0.0577	0.30	155	0.62	422.9	5.6				14.71	1.3	0.0574	3.8
61206-1-21.1	-0.000026	0.1090	0.36	313	0.39	1728.8	14.2	1789	14	3	3.24	0.8	0.1094	0.7
61206-1-22.1	-0.000033	0.0573	0.14	399	0.68	457.9	3.7				13.56	0.8	0.0578	1.8
61206-1-23.1	0.000065	0.0758	0.01	130	0.43	1088.7	14.8	1066	40	-2	5.44	1.4	0.0749	2.0
61206-1-24.1	0.000025	0.0768	-0.11	435	0.46	1140.0	8.0	1106	19	-3	5.18	0.7	0.0764	1.0
61206-1-25.1	0.000023	0.0557	0.08	851	0.68	415.4	2.3				15.02	0.6	0.0554	1.3
61206-1-26.1	0.000116	0.0971	0.66	95	0.48	1456.5	22.9	1538	36	5	3.93	1.6	0.0955	1.9
61206-1-27.1	0.000004	0.1296	0.02	378	0.23	2090.7	16.0	2092	10	0	2.61	0.8	0.1296	0.5
61206-1-28.1	-0.000027	0.1002	0.40	125	0.50	1563.0	20.5	1635	23	4	3.63	1.3	0.1006	1.2
61206-1-29.1	0.000012	0.0715	0.18	121	0.46	928.1	12.4	967	41	4	6.45	1.4	0.0713	2.0
61206-1-30.1	-0.000019	0.1018	-0.24	188	0.52	1694.4	18.7	1661	19	-2	3.33	1.1	0.1020	1.0
61206-1-31.1	0.000007	0.0608	0.07	798	0.59	612.9	3.3	629	22	2	10.02	0.6	0.0607	1.0

TABLE 1

(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ [1,2] (Ma)	err [3] (Ma)	$^{207}Pb/^{206}Pb$ [1,5] (Ma)	err [3] (Ma)	% disc.	$^{238}U/^{206}Pb$ [4]	err [3] (%)	$^{207}Pb/^{206}Pb$ [4]	err [3] (%)
Waits River Formation Sample 1 (I-89 southbound, UTM Zone 18 0692832E, 4899528N, NAD83 datum)														
61206-1-32.1	-0.000056	0.0918	0.75	70	0.79	1324.8	22.8	1479	35	10	4.35	1.8	0.0926	1.8
61206-1-33.1	-0.000036	0.1023	0.50	87	0.67	1584.6	24.7	1674	26	5	3.57	1.6	0.1028	1.4
61206-1-34.1	-0.000058	0.0734	-0.13	94	0.42	1053.6	16.2	1047	57	-1	5.63	1.6	0.0742	2.8
61206-1-35.1	0.000078	0.0998	-0.05	131	0.49	1627.9	20.5	1600	26	-2	3.49	1.3	0.0987	1.4
61206-1-36.1	-0.000208	0.0638	0.90	63	1.41	473.7	9.6				12.95	2.1	0.0668	4.0
61206-1-37.1	0.000026	0.0819	-0.11	196	0.48	1265.4	13.5	1234	28	-3	4.62	1.1	0.0815	1.4
61206-1-38.1	0.000055	0.0815	0.43	118	0.47	1143.3	15.3	1213	35	6	5.14	1.4	0.0807	1.8
61206-1-39.1	0.000003	0.1004	0.32	1930	0.01	1580.9	5.2	1632	7	3	3.59	0.3	0.1004	0.4
61206-1-40.1	-0.000211	0.0548	-0.21	59	1.01	472.6	9.7				13.12	2.1	0.0578	4.4
61206-1-41.1	0.000077	0.0585	-0.17	340	0.44	601.8	5.1				10.25	0.9	0.0574	1.9
61206-1-42.1	0.000012	0.0938	0.00	112	0.51	1503.4	20.1	1501	26	0	3.81	1.4	0.0936	1.4
61206-1-43.1	-0.000055	0.0754	-0.12	90	0.77	1106.1	17.0	1101	40	0	5.34	1.6	0.0762	2.0
61206-1-44.1	-0.000033	0.0566	0.02	366	1.18	471.2	3.9				13.18	0.8	0.0571	1.8
61206-1-45.1	0.000020	0.0555	-0.02	1265	0.43	440.7	1.9				14.14	0.4	0.0552	1.1
61206-1-46.1	-0.000052	0.0588	0.22	231	0.80	492.2	5.1				12.56	1.0	0.0596	2.2
61206-1-47.1	0.000073	0.1106	0.09	502	0.68	1797.1	11.4	1793	12	0	3.11	0.6	0.1096	0.6
61206-1-48.1	0.000104	0.0936	0.15	31	0.56	1472.9	37.6	1470	53	0	3.90	2.6	0.0921	2.8
61206-1-49.1	0.000005	0.2080	4.05	67	0.41	2577.1	50.2	2889	14	11	1.95	1.8	0.2079	0.9
61206-1-50.1	0.000009	0.0548	-0.12	990	0.20	443.8	2.3				14.05	0.5	0.0547	1.2
61206-1-51.1	0.000042	0.1018	-0.35	274	0.21	1711.2	15.2	1646	16	-4	3.30	0.9	0.1012	0.9
61206-1-52.1	0.000017	0.0729	-0.18	185	0.52	1051.8	11.0	1004	30	-5	5.65	1.1	0.0726	1.5
61206-1-53.1	0.001156	0.0601	0.05	133	0.55	593.5	8.0				10.58	1.8	0.0430	24.0
61206-1-54.1	0.000003	0.1105	0.24	556	0.29	1771.6	10.9	1806	10	2	3.15	0.6	0.1104	0.5
61206-1-55.1	0.000003	0.1941	1.61	121	1.01	2651.0	38.4	2777	11	5	1.93	1.3	0.1941	0.7
61206-1-56.1	0.000017	0.1071	0.26	393	0.25	1711.1	12.1	1747	12	2	3.28	0.7	0.1069	0.6
61206-1-57.1	0.000050	0.1105	0.40	152	0.42	1749.4	20.3	1797	19	3	3.20	1.2	0.1098	1.1
61206-1-58.1	-0.000007	0.1091	0.26	393	0.23	1746.6	12.4	1787	11	2	3.20	0.7	0.1092	0.6
61206-1-59.1	0.000012	0.0823	-0.17	658	0.47	1288.5	7.2	1250	13	-3	4.53	0.6	0.0822	0.7
61206-1-60.1	-0.000016	0.1069	0.27	195	0.54	1707.1	17.3	1751	17	3	3.29	1.0	0.1071	0.9

Table 1

(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ (Ma)[1,2]	err[3] (Ma)	$^{207}Pb/^{206}Pb$ (Ma)[1,5]	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$[4]	err[3] (%)	$^{207}Pb/^{206}Pb$[4]	err[3] (%)
Waits River Formation Sample 2 (I-91 median, UTM Zone 18 0709656E, 4818269N, NAD83 datum)														
61206-5-1.1	0.000099	0.0564	0.14	345	0.53	424.2	7.4				14.71	1.8	0.0550	2.6
61206-5-2.1	0.000061	0.0596	0.42	348	0.46	459.6	8.0				13.49	1.8	0.0587	2.1
61206-5-3.1	0.000042	0.0784	0.01	338	0.32	1155.1	19.5	1141	22	-1	5.10	1.7	0.0778	1.1
61206-5-4.1	0.000107	0.0582	-0.04	99	2.45	550.4	10.9				11.25	2.0	0.0566	3.6
61206-5-5.1	0.000012	0.1066	-0.01	221	0.32	1743.8	30.4	1739	16	0	3.22	1.8	0.1064	0.9
61206-5-6.1	0.000350	0.0754	0.41	265	0.29	986.3	17.0	940	56	-5	6.06	1.8	0.0704	2.8
61206-5-7.1	0.000009	0.0571	0.04	1187	0.21	482.7	8.0				12.86	1.7	0.0570	1.0
61206-5-8.1	0.000077	0.0579	0.15	337	0.48	479.5	8.3				12.95	1.8	0.0568	2.2
61206-5-9.1	-0.000003	0.1653	1.78	185	0.21	2340.0	43.9	2511	17	7	2.24	1.8	0.1653	1.0
61206-5-10.1	0.000034	0.0555	0.04	339	0.70	418.2	7.3				14.92	1.8	0.0550	2.1
61206-5-11.1	0.000147	0.0594	0.28	259	0.33	497.4	8.8				12.47	1.8	0.0573	2.9
61206-5-12.1	-0.000005	0.0794	0.35	307	0.37	1106.4	18.7	1183	20	6	5.32	1.7	0.0794	1.0
61206-5-13.1	-0.000037	0.1011	0.02	150	1.01	1642.2	29.4	1654	21	1	3.44	1.8	0.1017	1.2
61206-5-14.1	0.000082	0.0566	0.02	191	0.47	467.6	8.5				13.31	1.9	0.0554	2.9
61206-5-15.1	0.000021	0.1007	-0.02	141	0.35	1639.1	29.5	1631	21	0	3.46	1.9	0.1004	1.1
61206-5-16.1	0.000054	0.0926	0.47	314	0.65	1395.6	23.6	1464	18	5	4.12	1.7	0.0919	0.9
61206-5-17.1	-0.000026	0.0564	0.03	149	0.69	459.7	8.6				13.52	1.9	0.0568	2.8
61206-5-18.1	0.000145	0.0573	0.09	1864	0.06	472.5	7.7				13.17	1.7	0.0551	1.3
61206-5-19.1	-0.000025	0.0773	0.37	66	0.92	1049.1	21.2	1139	47	8	5.64	2.1	0.0777	2.3
61206-5-20.1	0.000024	0.0549	-0.10	1280	0.25	441.3	7.3				14.13	1.7	0.0546	1.2
61206-5-21.1	-0.000004	0.0598	0.45	429	0.66	459.2	7.8				13.48	1.7	0.0599	1.6
61206-5-22.1	-0.000025	0.0826	0.41	55	0.52	1175.1	24.4	1267	45	7	4.98	2.1	0.0829	2.3
61206-5-23.1	0.000011	0.0809	0.04	535	0.25	1210.9	19.9	1216	19	0	4.84	1.7	0.0808	1.0
61206-5-24.1	0.000019	0.0603	0.12	525	0.86	578.9	9.7				10.63	1.7	0.0600	1.3
61206-5-25.1	0.000045	0.0604	0.04	390	0.26	607.6	10.3	595	34	-2	10.12	1.7	0.0598	1.6
61206-5-26.1	0.000097	0.0753	0.14	101	0.44	1044.1	19.6	1039	47	-1	5.69	1.9	0.0739	2.3
61206-5-27.1	0.000082	0.0625	0.05	322	0.50	676.2	11.6	650	40	-4	9.05	1.8	0.0613	1.8
61206-5-28.1	-0.000043	0.0923	0.78	30	0.71	1331.0	32.0	1486	54	10	4.32	2.5	0.0929	2.9
61206-5-29.1	-0.000008	0.1922	0.86	66	0.40	2694.1	61.8	2762	15	2	1.91	2.0	0.1923	0.9
61206-5-30.1	0.000048	0.0825	0.11	229	0.56	1235.4	21.2	1242	24	1	4.73	1.8	0.0818	1.2
61206-5-31.1	0.000076	0.1000	-0.36	158	0.79	1681.0	30.0	1604	22	-5	3.37	1.8	0.0989	1.2

Table 1
(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ (Ma)[1,2]	err[3] (Ma)	$^{207}Pb/^{206}Pb$ (Ma)[1,5]	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$[4]	err[3] (%)	$^{207}Pb/^{206}Pb$[4]	err[3] (%)
Waits River Formation Sample 2 (I-91 median, UTM Zone 18 0709656E, 4818269N, NAD83 datum)														
61206-5-32.1	0.000010	0.0780	0.07	658	0.27	1132.9	18.6	1144	18	1	5.20	1.7	0.0779	0.9
61206-5-33.1	0.000020	0.0626	0.01	823	0.42	692.6	11.4	685	21	-1	8.82	1.7	0.0623	1.0
61206-5-34.1	-0.000061	0.0556	-0.02	68	0.65	442.5	9.6				14.06	2.2	0.0565	4.3
61206-5-35.1	-0.000081	0.0636	0.79	44	0.57	498.7	11.8				12.32	2.4	0.0647	4.6
61206-5-36.1	-0.000003	0.1156	-0.26	259	0.66	1924.0	33.4	1890	12	-2	2.88	1.8	0.1156	0.7
61206-5-37.1	0.000074	0.0546	-0.12	369	0.54	433.2	7.5				14.42	1.8	0.0535	2.3
61206-5-38.1	-0.000003	0.0793	0.07	419	0.24	1163.4	19.3	1180	17	1	5.05	1.7	0.0793	0.9
61206-5-39.1	0.000061	0.0633	-0.13	383	0.43	755.7	12.8	689	31	-10	8.06	1.7	0.0624	1.5
61206-5-40.1	0.000061	0.0788	0.02	149	0.41	1162.3	20.8	1145	32	-2	5.07	1.9	0.0779	1.6
61206-5-41.1	0.000140	0.0600	0.39	104	0.40	484.6	9.5				12.79	2.0	0.0579	4.0
61206-5-42.1	0.000084	0.0601	0.35	792	0.26	499.8	8.3				12.38	1.7	0.0589	1.5
61206-5-43.1	0.000047	0.0805	0.07	229	0.44	1196.4	20.5	1194	24	0	4.90	1.8	0.0799	1.2
61206-5-44.1	-0.000029	0.0547	-0.23	124	0.39	474.0	9.0				13.13	1.9	0.0551	3.0
61206-5-45.1	-0.000017	0.0613	0.45	204	0.50	517.9	9.3				11.90	1.8	0.0616	2.1
61206-5-46.1	0.000039	0.0815	0.00	293	0.37	1234.0	20.8	1221	21	-1	4.74	1.7	0.0810	1.0
61206-5-47.1	0.000073	0.0730	-0.19	138	0.51	1055.8	18.9	984	38	-7	5.64	1.9	0.0719	1.8
61206-5-48.1	-0.000005	0.0926	0.09	201	0.63	1463.8	25.3	1481	19	1	3.92	1.8	0.0926	1.0
61206-5-49.1	0.000123	0.0768	0.42	75	0.44	1023.5	20.0	1071	52	4	5.80	2.0	0.0751	2.6
61206-5-50.1	0.000029	0.0731	-0.14	932	0.21	1049.3	17.0	1006	14	-4	5.67	1.7	0.0727	0.7
61206-5-51.1	0.000113	0.0621	0.00	117	1.62	677.1	12.7	620	68	-9	9.05	1.9	0.0604	3.1
61206-5-52.1	-0.000020	0.0755	0.15	74	0.83	1048.7	20.5	1089	43	4	5.65	2.0	0.0758	2.1
61206-5-53.1	0.000072	0.0749	-0.07	327	0.44	1083.0	18.2	1039	25	-4	5.48	1.7	0.0739	1.2
61206-5-54.1	0.000037	0.0803	0.13	101	1.29	1178.1	22.0	1192	35	1	4.98	1.9	0.0798	1.8
61206-5-55.1	-0.000023	0.0545	-0.25	162	0.56	471.6	8.7				13.20	1.9	0.0548	2.6
61206-5-56.1	0.000042	0.0554	0.00	613	0.43	429.8	7.2				14.52	1.7	0.0548	1.5
61206-5-57.1	-0.000088	0.0995	0.05	72	0.53	1606.4	31.5	1638	45	2	3.53	2.0	0.1007	2.4
61206-5-58.1	-0.000009	0.0907	0.76	137	0.43	1296.3	23.2	1442	27	10	4.45	1.9	0.0908	1.4
61206-5-59.1	0.000025	0.0882	0.03	126	0.43	1381.5	24.9	1380	26	0	4.18	1.9	0.0879	1.4
61206-5-60.1	0.000041	0.0769	0.18	252	0.33	1077.2	18.4	1103	24	2	5.49	1.8	0.0763	1.2

Table 1

(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ [1,2] (Ma)	err[3] (Ma)	$^{207}Pb/^{206}Pb$ [1,5] (Ma)	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$ [4]	err[3] (%)	$^{207}Pb/^{206}Pb$ [4]	err[3] (%)
Gile Mountain Formation Sample 3 (I-89 northbound Exit 2 onramp, UTM Zone 18 0704909E, 4851349N, NAD83 datum)														
61206-3-1.1	-0.000003	0.0853	-0.07	1324	1.01	1336.3	5.2	1324	9	-1	4.34	0.4	0.0854	0.4
61206-3-2.1	0.000003	0.0552	-0.06	2329	0.64	440.2	1.5				14.16	0.3	0.0552	1.0
61206-3-3.1	-0.000009	0.0737	-0.06	612	0.34	1045.5	6.1	1036	16	-1	5.68	0.6	0.0738	0.8
61206-3-4.1	0.000007	0.0866	-0.35	129	0.38	1416.3	17.7	1349	27	-5	4.08	1.3	0.0865	1.4
61206-3-5.1	0.000003	0.0559	-0.10	1025	0.38	480.6	2.4				12.93	0.5	0.0558	1.1
61206-3-6.1	0.000060	0.0564	0.15	202	0.72	418.7	4.6				14.90	1.1	0.0555	2.7
61206-3-7.1	-0.000001	0.1053	0.47	2278	0.14	1646.8	4.8	1720	5	4	3.42	0.3	0.1053	0.3
61206-3-8.1	-0.000009	0.0772	0.02	513	0.20	1122.4	7.1	1129	16	1	5.26	0.7	0.0773	0.8
61206-3-9.1	-0.000073	0.0754	0.19	113	0.32	1036.4	13.5	1106	43	6	5.72	1.3	0.0764	2.2
61206-3-10.1	0.000038	0.1015	0.47	225	0.30	1576.0	14.8	1643	18	4	3.60	1.0	0.1010	1.0
61206-3-11.1	0.007768	0.1921	11.24	1669	0.29	*1539.3*	*8.9*	1268	117	-21	3.76	0.6	0.0830	6.0
61206-3-12.1	-0.000008	0.0604	0.04	1250	0.06	605.5	2.6	622	18	3	10.15	0.4	0.0605	0.8
61206-3-13.1	0.000001	0.1084	0.54	634	0.47	1692.9	9.5	1773	9	5	3.31	0.6	0.1084	0.5
61206-3-14.1	-0.000097	0.0614	0.38	107	0.59	541.1	8.0				11.36	1.5	0.0628	2.9
61206-3-15.1	-0.000012	0.1882	2.52	163	0.20	2515.6	30.6	2727	10	8	2.04	1.1	0.1883	0.6
61206-3-16.1	0.001350	0.0619	-2.07	290	0.05	*1181.2*	*15.8*	-229	435	616	5.19	1.6	0.0420	17.3
61206-3-17.1	-0.000004	0.0778	0.21	1322	0.17	1094.0	4.3	1142	10	4	5.39	0.4	0.0778	0.5
61206-3-18.1	-0.000019	0.0767	0.02	399	0.40	1108.3	8.0	1119	20	1	5.33	0.7	0.0769	1.0
61206-3-19.1	0.000002	0.0746	0.19	475	0.16	1013.4	6.6	1056	18	4	5.86	0.7	0.0745	0.9
61206-3-20.1	-0.000009	0.0952	0.10	381	0.35	1515.0	10.8	1534	14	1	3.77	0.7	0.0953	0.7
61206-3-21.1	-0.000037	0.0731	0.05	138	0.34	1004.7	11.9	1031	34	3	5.92	1.2	0.0736	1.7
61206-3-22.1	0.000324	0.0772	0.36	581	0.34	1046.2	6.2	1002	31	-4	5.69	0.6	0.0726	1.5
61206-3-23.1	0.000044	0.0739	0.12	162	0.38	1010.7	11.4	1020	33	1	5.89	1.2	0.0732	1.6
61206-3-24.1	0.000020	0.0761	-0.09	714	0.50	1116.3	5.9	1089	14	-2	5.30	0.5	0.0758	0.7
61206-3-25.1	-0.000052	0.0824	0.18	115	0.34	1218.6	19.0	1271	36	4	4.79	1.6	0.0831	1.9
61206-3-26.1	-0.000012	0.0929	0.02	376	0.43	1481.6	12.5	1488	16	0	3.87	0.9	0.0930	0.9
61206-3-27.1	-0.000603	0.0578	0.12	24	0.28	485.5	17.6				12.63	3.7	0.0665	6.3
61206-3-28.1	-0.000029	0.0745	0.11	244	0.37	1030.7	11.1	1067	29	3	5.76	1.1	0.0749	1.5
61206-3-29.1	-0.000158	0.0538	-0.33	96	0.54	469.8	8.7				13.23	1.9	0.0561	3.9
61206-3-30.1	-0.000085	0.0738	0.12	81	0.16	1008.0	18.6	1069	50	6	5.89	1.9	0.0750	2.5
61206-3-31.1	0.000151	0.0558	0.07	909	0.88	422.4	2.5				14.80	0.6	0.0536	2.0

TABLE 1
(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$[1,2] (Ma)	err[3] (Ma)	$^{207}Pb/^{206}Pb$[1,5] (Ma)	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$[4]	err[3] (%)	$^{207}Pb/^{206}Pb$[4]	err[3] (%)
Gile Mountain Formation Sample 3 (I-89 northbound Exit 2 onramp, UTM Zone 18 0704909E, 4851349N, NAD83 datum)														
61206-3-32.1	0.000011	0.0919	-0.20	413	0.34	1501.0	12.2	1462	16	-3	3.82	0.8	0.0918	0.8
61206-3-33.1	0.000030	0.0738	0.09	245	0.31	1014.8	10.6	1024	31	1	5.86	1.1	0.0733	1.5
61206-3-34.1	0.000063	0.1042	1.56	905	0.19	*1443.4*	*7.9*	1685	11	14	3.93	0.6	0.1033	0.6
61206-3-35.1	-0.000174	0.0765	0.10	38	0.59	1085.1	29.0	1170	76	7	5.43	2.7	0.0789	3.9
61206-3-36.1	-0.000026	0.0775	0.00	237	0.37	1133.4	12.0	1142	27	1	5.20	1.1	0.0778	1.4
61206-3-37.1	-0.000055	0.0774	0.00	122	0.34	1131.8	17.1	1153	39	2	5.21	1.6	0.0782	2.0
61206-3-38.1	-0.000191	0.0595	0.35	77	0.28	480.8	9.6				12.82	2.0	0.0623	4.0
61206-3-39.1	-0.000109	0.0825	0.73	55	0.54	*1104.8*	*24.3*	1293	52	15	5.30	2.3	0.0840	2.7
61206-3-40.1	-0.000026	0.1756	0.16	91	0.39	2598.6	49.0	2615	16	1	2.01	1.7	0.1760	0.9
61206-3-41.1	0.000006	0.0579	0.21	574	0.50	460.7	3.4				13.47	0.7	0.0578	1.6
61206-3-42.1	-0.000009	0.0819	0.34	668	0.27	1171.9	7.4	1245	17	6	5.00	0.6	0.0820	0.9
61206-3-43.1	-0.000018	0.0728	-0.19	364	0.30	1050.3	8.9	1014	24	-4	5.66	0.9	0.0730	1.2
61206-3-44.1	0.000019	0.1136	1.55	555	0.09	*1626.8*	*11.0*	1853	11	12	3.43	0.7	0.1133	0.6
61206-3-45.1	0.000022	0.1171	0.20	264	1.04	1885.6	19.0	1907	15	1	2.94	1.0	0.1168	0.8
61206-3-46.1	-0.000091	0.0778	-0.20	63	0.36	1183.8	24.0	1174	50	-1	4.96	2.1	0.0791	2.5
61206-3-47.1	-0.000018	0.1944	2.22	127	0.52	2602.0	41.6	2781	12	6	1.97	1.4	0.1946	0.8
61206-3-48.1	-0.000018	0.1019	0.06	216	0.80	1649.0	17.8	1663	19	1	3.43	1.1	0.1021	1.0
61206-3-49.1	0.000004	0.1129	0.02	190	0.35	1844.3	21.4	1846	18	0	3.02	1.2	0.1128	1.0
61206-3-50.1	-0.000011	0.0790	0.09	554	0.39	1153.2	8.0	1176	20	2	5.10	0.7	0.0791	1.0
61206-3-51.1	0.000034	0.0918	-0.13	3650	0.14	1487.0	4.0	1454	9	-2	3.86	0.3	0.0913	0.5
61206-3-52.1	-0.000015	0.0809	0.15	368	0.35	1187.7	9.9	1223	20	3	4.93	0.9	0.0811	1.0
61206-3-53.1	-0.000009	0.1173	0.54	397	0.39	1840.8	14.9	1917	12	4	3.01	0.8	0.1174	0.7
61206-3-54.1	0.000026	0.0574	0.14	793	0.33	464.8	2.9				13.36	0.6	0.0571	1.4
61206-3-55.1	-0.000100	0.0547	-0.30	216	0.63	496.1	5.9				12.52	1.2	0.0561	3.4
61206-3-56.1	-0.000042	0.0761	0.02	168	0.54	1095.3	14.2	1114	34	2	5.39	1.3	0.0767	1.7
61206-3-57.1	-0.000209	0.0573	0.29	76	1.02	411.2	8.3				15.08	2.0	0.0604	4.2
61206-3-58.1	0.000003	0.2638	9.18	222	0.40	*2679.2*	*33.2*	3269	7	18	1.76	1.1	0.2637	0.5
61206-3-59.1	-0.000032	0.1072	0.36	115	0.81	1697.9	24.9	1760	24	4	3.31	1.5	0.1076	1.3
61206-3-60.1	-0.000047	0.1132	0.07	75	1.43	1840.3	33.6	1861	28	1	3.02	1.8	0.1138	1.5

Table 1

(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ [1,2] (Ma)	err[3] (Ma)	$^{207}Pb/^{206}Pb$ [1,5] (Ma)	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$ [4]	err[3] (%)	$^{207}Pb/^{206}Pb$ [4]	err[3] (%)
Gile Mountain Formation Sample 4 (White River, UTM Zone 18 0698121E, 4855550N, NAD83 datum)														
61206-2-1.1	0.000137	0.0573	0.29	413	0.31	409.6	7.2				15.24	1.8	0.0553	3.0
61206-2-2.1	-0.000005	0.1116	0.60	215	0.64	1737.4	30.8	1826	16	5	3.21	1.8	0.1116	0.9
61206-2-3.1	-0.000009	0.0582	0.26	505	0.84	454.0	7.8				13.67	1.7	0.0583	1.6
61206-2-4.1	-0.000025	0.0591	-0.12	142	1.12	607.5	11.5	584	58	-4	10.13	1.9	0.0595	2.7
61206-2-5.1	-0.000018	0.0562	0.12	275	0.38	421.5	7.6				14.78	1.8	0.0565	2.3
61206-2-6.1	-0.000012	0.0955	0.40	114	0.48	1468.5	27.7	1542	29	5	3.89	1.9	0.0957	1.6
61206-2-7.1	0.000099	0.0598	0.56	267	0.25	422.4	7.7				14.71	1.8	0.0583	3.0
61206-2-8.1	0.000029	0.0564	0.04	446	0.23	455.6	7.8				13.66	1.8	0.0560	1.8
61206-2-9.1	-0.000004	0.1294	0.48	221	0.39	2031.6	36.6	2091	14	3	2.69	1.8	0.1295	0.8
61206-2-10.1	-0.000026	0.0552	0.04	200	0.29	408.3	7.6				15.28	1.9	0.0556	2.8
61206-2-11.1	0.000144	0.0567	0.23	368	0.36	404.5	7.1				15.45	1.8	0.0546	2.7
61206-2-12.1	-0.000009	0.0831	0.19	171	0.27	1233.0	22.1	1275	27	3	4.73	1.9	0.0833	1.4
61206-2-13.1	-0.000026	0.0723	-0.06	79	0.71	1007.7	20.4	1005	50	0	5.91	2.1	0.0727	2.5
61206-2-14.1	-0.000014	0.0554	0.07	380	0.40	403.4	7.1				15.47	1.8	0.0556	2.0
61206-2-15.1	-0.000008	0.0538	-0.15	634	0.36	413.5	7.0				15.12	1.7	0.0539	1.6
61206-2-16.1	-0.000064	0.0756	0.05	28	0.59	1073.0	27.9	1108	75	3	5.51	2.7	0.0765	3.8
61206-2-17.1	0.000010	0.0937	-0.01	323	0.40	1502.9	25.5	1498	16	0	3.81	1.8	0.0935	0.9
61206-2-18.1	-0.000018	0.0733	0.13	108	0.24	993.1	19.0	1029	42	4	5.99	2.0	0.0736	2.1
61206-2-19.1	-0.000014	0.0568	0.22	362	0.17	412.3	7.3				15.10	1.8	0.0570	2.1
61206-2-20.1	-0.000006	0.0956	0.17	217	0.68	1511.0	26.4	1541	19	2	3.78	1.8	0.0957	1.0
61206-2-21.1	-0.000008	0.0578	0.08	496	0.71	496.1	8.4				12.49	1.7	0.0579	1.5
61206-2-22.1	-0.000007	0.0854	0.02	197	0.68	1322.1	23.3	1328	24	0	4.39	1.8	0.0855	1.2
61206-2-23.1	0.000038	0.1230	0.68	205	0.63	1910.7	34.2	1993	15	4	2.88	1.8	0.1225	0.9
61206-2-24.1	-0.000024	0.0715	-0.33	81	0.45	1047.7	21.0	981	61	-7	5.68	2.1	0.0718	3.0
61206-2-25.1	0.000057	0.0703	0.09	107	0.90	916.5	17.6	914	49	0	6.55	2.0	0.0695	2.4
61206-2-26.1	0.000037	0.0556	0.10	442	0.29	406.5	7.0				15.36	1.8	0.0551	2.0
61206-2-27.1	0.000043	0.0559	0.09	590	0.14	418.5	7.1				14.91	1.7	0.0553	1.8
61206-2-28.1	0.000039	0.0924	-0.14	447	0.34	1499.6	25.1	1464	15	-2	3.83	1.7	0.0918	0.8
61206-2-29.1	0.000095	0.0889	1.04	53	2.75	1200.1	25.9	1373	74	13	4.84	2.2	0.0876	3.8
61206-2-30.1	0.000020	0.0553	0.03	1853	0.44	413.7	6.8				15.09	1.7	0.0550	0.9
61206-2-31.1	0.000078	0.0572	0.28	418	0.16	410.5	7.1				15.19	1.8	0.0561	2.2

TABLE 1

(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$ [1,2] (Ma)	err[3] (Ma)	$^{207}Pb/^{206}Pb$ [1,5] (Ma)	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$ [4]	err[3] (%)	$^{207}Pb/^{206}Pb$ [4]	err[3] (%)
Gile Mountain Formation Sample 4 (White River, UTM Zone 18 0698121E, 4855550N, NAD83 datum)														
61206-2-32.1	0.000026	0.1133	-0.49	151	0.81	1920.4	35.4	1848	19	-4	2.90	1.9	0.1130	1.0
61206-2-33.1	0.000487	0.0644	0.98	25	1.13	472.0	14.1				13.15	3.0	0.0573	10.7
61206-2-34.1	0.000027	0.0949	-0.19	185	0.50	1557.0	27.7	1518	24	-3	3.67	1.8	0.0945	1.3
61206-2-35.1	0.000124	0.0695	-0.03	114	0.44	921.4	17.5	859	55	-7	6.52	2.0	0.0677	2.7
61206-2-36.1	0.000079	0.0565	0.14	722	0.37	428.3	7.2				14.56	1.7	0.0554	1.9
61206-2-37.1	0.000128	0.0776	0.48	93	0.70	1029.2	20.1	1089	52	5	5.76	2.0	0.0758	2.6
61206-2-38.1	0.000039	0.0574	0.32	383	0.14	406.4	7.1				15.33	1.8	0.0569	2.1
61206-2-39.1	-0.000015	0.0597	-0.15	220	0.61	636.3	11.4	599	45	-6	9.65	1.8	0.0599	2.1
61206-2-40.1	0.000091	0.0742	-0.07	131	0.69	1063.7	19.7	1012	43	-5	5.59	1.9	0.0729	2.1
61206-2-41.1	0.000051	0.0571	0.10	695	0.18	466.9	7.9				13.31	1.7	0.0564	1.6
61206-2-42.1	0.000066	0.0836	-0.04	212	0.35	1291.6	22.8	1262	43	-2	4.51	1.8	0.0827	2.2
61206-2-43.1	0.000055	0.1232	1.74	52	0.70	*1766.5*	*38.5*	1992	35	11	3.12	2.2	0.1224	2.0
61206-2-44.1	0.000026	0.0575	0.19	499	1.17	452.5	7.7				13.73	1.7	0.0572	1.7
61206-2-45.1	0.000056	0.0743	0.16	229	0.20	1011.7	17.7	1027	32	2	5.88	1.8	0.0735	1.6
61206-2-46.1	0.000067	0.0829	0.40	270	0.45	1184.5	20.3	1244	25	5	4.94	1.8	0.0819	1.3
61206-2-47.1	0.000078	0.0559	0.13	398	0.48	407.5	7.1				15.33	1.8	0.0548	2.3
61206-2-48.1	-0.000014	0.0717	0.25	154	0.40	919.3	16.8	984	37	7	6.51	1.9	0.0719	1.8
61206-2-49.1	-0.000020	0.0824	0.02	77	0.57	1251.6	24.9	1262	40	1	4.66	2.1	0.0827	2.0
61206-2-50.1	0.000058	0.0567	0.02	207	0.51	475.9	8.7				13.06	1.9	0.0559	3.1
61206-2-51.1	0.000044	0.1013	0.40	171	1.31	1584.7	28.4	1638	21	3	3.58	1.8	0.1007	1.1
61206-2-52.1	0.000079	0.0770	0.65	236	1.32	974.7	17.0	1092	32	11	6.10	1.8	0.0759	1.6
61206-2-53.1	-0.000010	0.0766	0.20	176	0.53	1064.3	18.9	1113	29	4	5.56	1.8	0.0767	1.5
61206-2-54.1	0.000016	0.0715	-0.12	317	0.12	998.9	16.9	964	24	-4	5.97	1.8	0.0712	1.2
61206-2-55.1	-0.000003	0.0891	0.13	398	0.34	1381.3	23.1	1407	15	2	4.18	1.7	0.0891	0.8
61206-2-56.1	0.000163	0.0571	0.22	473	0.66	423.4	7.3				14.74	1.8	0.0547	2.4
61206-2-57.1	0.000230	0.0693	-0.05	67	0.37	919.4	18.7	806	79	-14	6.55	2.1	0.0660	3.8
61206-2-58.1	0.000067	0.1347	0.01	89	0.80	2159.7	42.9	2149	20	0	2.52	2.0	0.1339	1.1
61206-2-59.1	0.000479	0.0616	0.82	101	0.53	408.3	8.3				15.30	2.1	0.0546	8.5
61206-2-60.1	-0.000010	0.0618	0.16	293	0.71	622.5	10.8	674	35	8	9.85	1.8	0.0620	1.7

Table 1

(continued)

Lab sample #	measured $^{204}Pb/^{206}Pb$	measured $^{207}Pb/^{206}Pb$	% common ^{206}Pb	U (ppm)	Th/U	$^{206}Pb/^{238}U$[1,2] (Ma)	err[3] (Ma)	$^{207}Pb/^{206}Pb$[1,5] (Ma)	err[3] (Ma)	% disc.	$^{238}U/^{206}Pb$[4]	err[3] (%)	$^{207}Pb/^{206}Pb$[4]	err[3] (%)
Gile Mountain Formation Sample 4 (hand picked grains)														
HP61206-2-1.1	0.000111	0.0584	0.37	825	0.05	*428.7*	*7.2*				14.52	1.7	0.0568	1.6
HP61206-2-2.1	0.000362	0.0585	0.50	464	0.21	*389.9*	*6.7*				16.06	1.7	0.0532	3.5
HP61206-2-3.1	0.000173	0.0559	0.13	290	0.34	407.9	7.2				15.34	1.8	0.0534	3.1
HP61206-2-4.1	0.000018	0.0542	-0.06	896	0.18	400.5	6.7				15.61	1.7	0.0539	2.1
HP61206-2-5.1	0.000121	0.0574	0.27	555	0.22	422.3	7.2				14.76	1.7	0.0556	2.1
HP61206-2-6.1	-0.000017	0.0546	-0.01	310	0.13	400.5	7.0				15.60	1.8	0.0549	2.0
HP61206-2-7.1	0.000063	0.0564	0.19	886	0.19	407.3	6.8				15.32	1.7	0.0555	1.4
HP61206-2-8.1	0.000013	0.0551	0.04	1993	0.07	403.3	6.6				15.49	1.7	0.0549	0.8
HP61206-2-9.1	0.000144	0.0563	0.18	340	0.56	406.1	7.1				15.39	1.8	0.0542	2.6
HP61206-2-10.1	-0.000047	0.0540	-0.03	224	0.08	*383.4*	*7.3*				16.31	1.9	0.0547	3.3
HP61206-2-11.1	0.000201	0.0574	0.29	436	0.31	417.4	7.1				14.96	1.7	0.0545	2.9
HP61206-2-12.1	-0.000013	0.0560	0.09	405	0.25	421.8	7.2				14.77	1.7	0.0562	2.3
HP61206-2-13.1	0.000091	0.0539	-0.13	311	0.23	411.2	7.2				15.23	1.8	0.0526	2.8
HP61206-2-14.1	0.000032	0.0560	0.14	717	0.26	407.9	6.8				15.30	1.7	0.0555	1.4
HP61206-2-15.1	0.000018	0.0541	-0.16	653	0.22	*431.5*	*7.3*				14.47	1.7	0.0539	1.6
HP61206-2-16.1	0.000055	0.0546	-0.03	997	0.08	406.3	6.7				15.39	1.7	0.0538	1.3

All analyses performed on the USGS/Stanford ion microprobe (SHRIMP-RG).

[1] $^{206}Pb/^{238}U$ ages corrected for common Pb using the ^{207}Pb-correction method; $^{207}Pb/^{206}Pb$ ages corrected for common Pb using the ^{204}Pb-correction method.

[2] Ages excluded from Relative Probability plots due to high U and reverse discordance or discordance >15%, including errors (shown in italics). Decay constants from Steiger and Jager (1977).

[3] 1-sigma errors.

[4] Radiogenic ratios, corrected for common Pb using the ^{204}Pb-correction method, based on the Stacey and Kramers (1975) model.

[5] Listed only for ages >600 Ma.

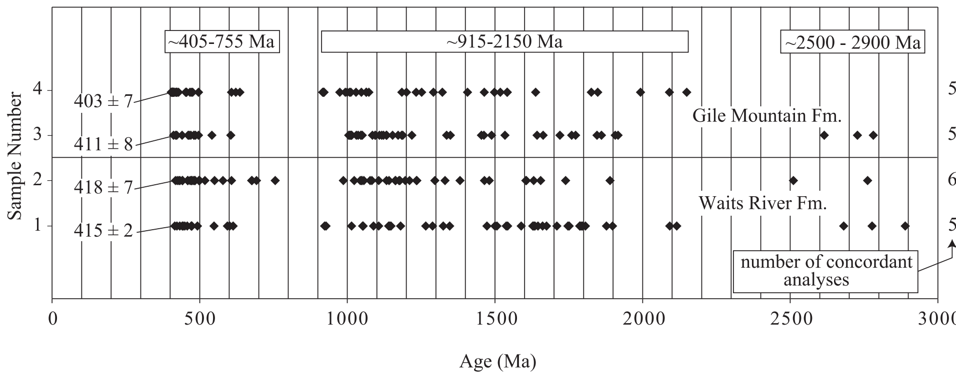


Fig. 4. Summary plot of all 231 concordant detrital zircon ages given in table 1. The number of analyses is indicated in the right margin. The ages of the youngest analyses are indicated for each of the four samples. Errors are not plotted but generally fall within the size of the symbol. See figure 5 for relative probability plots. For zircon analyses yielding ages <1200 Ma, $^{206}Pb/^{238}U$ ages are plotted and for zircons >1200 Ma, $^{207}Pb/^{206}Pb$ ages are plotted.

SHRIMP analyses of 60 zircons from this sample yielded 58 concordant analyses (table 1; figs. 4 and 6). These data approximate three age populations: 1) 415 to 500 Ma, 2) 550 to 615 Ma, and 3) 925 to 2120 Ma, with three grains >2600 Ma (figs. 4, 5, and 6A).

Sample 2 was collected from a light-gray quartzite interbedded within gray phyllite and siliceous marble of the Waits River Formation in the eastern part of the basin just north of Mt. Ascutney in Windsor along I-91 (Walsh and others, 1996a; DSwl, fig. 2). Zircons separated from this quartzite have rounded edges but some grains have aspect ratios up to 4:1. Grain size typically is coarser than in the previous sample with diameters of 20 to 100 μm. CL imaging reveals oscillatory and sector zoning with cores, mantles and rims commonly truncated at grain boundaries (fig. 6B).

SHRIMP analyses of zircons from this sample yielded 60 concordant analyses (table 1; figs. 4 and 6). These data approximate three age populations: 1) 420 to 500 Ma, 2) 520 to 750 Ma, and 3) 990 to 1900 Ma, with two grains >2500 Ma (figs. 4, 5, and 6B).

Gile Mountain Formation

Sample 3, from the Gile Mountain Formation, was collected from a light-gray feldspathic quartzite interbedded with less abundant gray schist in the eastern part of the basin near exit 2 on I-89 in Sharon, Vermont (see Day I, Stop 5 of Slack and Offield, 1993; DgS, fig. 2). Most zircons separated from this quartzite are subangular to rounded, plus rare elongate grains having an aspect ratio ~4:1. Grain size ranges from 10 to 40 μm in diameter. CL imaging reveals common oscillatory and sector zoned cores in individual grains (fig. 6C). Zoned mantles and rims are truncated by metamorphic overgrowths ~1 to 3 μm thick that occur on all grains (fig. 6C).

SHRIMP analyses of zircons from sample 3 yielded 54 concordant analyses (table 1; figs. 4 and 6). These data approximate two age populations: 1) 410 to 500 Ma, and 2) 1000 to 1900 Ma, plus two Neoproterozoic grains and three Archean grains (figs. 4, 5, and 6C).

Sample 4 was collected from the Gile Mountain Formation in the western part of the basin in the core of the Townshend-Brownington syncline (fig. 2). Here rhythmically-bedded quartzite is exposed in the White River near Royalton, Vermont (see Day I, Stop 2 of Slack and Offield, 1993; Dgr, fig. 2). Sample 4 was collected from the coarser

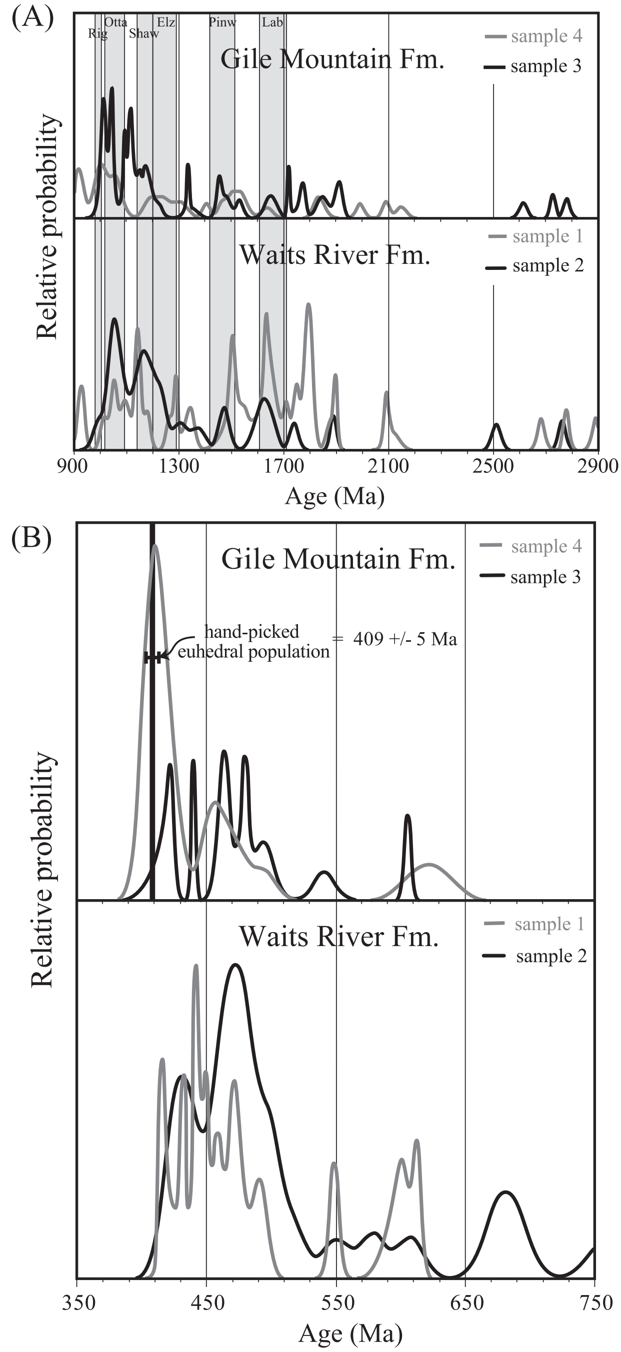


Fig. 5. Relative probability plots of detrital zircon ages. For zircon analyses yielding ages <1200 Ma, $^{206}Pb/^{238}U$ ages are plotted and for zircons >1200 Ma, $^{207}Pb/^{206}Pb$ ages are plotted. (A) All concordant ages older than 900 Ma. Abbreviations: Rig.—Rigolet; Otta.—Ottawan; Shaw.—Shawinigan; Elz.—Elzevirian; Pinw.—Pinwarian; Lab.—Labradorian. (B) All concordant ages younger than 750 Ma. Weighted average of ages obtained from hand-picked euhedral grains from sample 4 is shown (bold black line).

basal parts of the beds. Most zircons from this sample are rounded spherical grains 10 to 40 μm in diameter. However, several grains are euhedral, doubly-terminated and elongate, with inclusion tubes and aspect ratios up to ~7:1. CL imaging reveals oscillatory and sector zoning in individual grains; oscillatory-zoned cores typically have at least one overgrowth that also displays oscillatory zoning (figs. 6D and 7).

SHRIMP analyses of randomly selected detrital zircons from this sample yielded 59 concordant analyses (table 1, figs. 4 and 6). These data approximate three age groups: 1) ~405 to 500 Ma, 2) ~600 to 640 Ma, and 3) 915 to 2150 Ma (figs. 4, 5, and 6D). In addition, euhedral zircons handpicked from this sample were analyzed on their tips (table 1). SHRIMP analyses of these euhedral grains yielded 16 concordant analyses of which 12 represent a coherent age population with a weighted average age of 409 ± 5 Ma (fig. 7).

DISCUSSION

Previous studies highlight the uncertainty in the depositional ages of rocks of the CVS and suggest deposition during broadly Silurian-Devonian times (for example, Doll and others, 1961; Hatch and others, 1988; Lyons and others, 1997). Moreover, the provenance of these sediments is largely unknown (for example, Hatch, 1988a; Rankin and others, 2007).

Correlation of Units

Facies distributions identified within the CVS (Hatch, 1988a) suggest that rocks mapped as Waits River and Gile Mountain may not correlate across the basin. To test these traditionally accepted correlations (Doll and others, 1961) we collected samples from the eastern and western parts of the basin and we compare the relative probability age distribution plots of all four samples (fig. 5).

Waits River Formation.—Relative probability plots for both samples from the Waits River Formation are similar. The plot from sample 2 in the east reveals two broad peaks within the range ~400 to 500 Ma (fig. 5). The western sample (sample 1) appears to have multiple sharp peaks in the same age range. However, Silurian-Ordovician peaks in this sample are defined by only one or two zircons and result in sharp peaks because of relatively low analytical uncertainty (table 1). Thus, zircons from both samples can be grouped into two populations: 1) ~415 to 445 Ma and 2) ~460 to 500 Ma (table 1). The same situation arises for zircons between ~550 Ma and 750 Ma. Broad peaks in the eastern sample and sharp peaks in the western sample (fig. 5) represent similar age distributions (table 1).

Relative probability plots of zircons older than 900 Ma are similar for the eastern and western Waits River Formation samples. Peaks at ~1050 Ma, 1150 Ma, 1500 Ma, 1630 Ma, and 1750 Ma are present in both samples (fig. 5). Archean zircons also occur in both samples. These results support the correlation of rocks mapped as Waits River Formation in the eastern and western parts of the CVS. Similar lithologies and age distributions suggest that these sediments were likely laterally continuous across the basin and were deposited at about the same time in similar depositional environments.

Gile Mountain Formation.—At first glance, the relative probability plots for samples of the Gile Mountain Formation appear similar to one another. Eastern and western samples contain abundant Mesoproterozoic zircons with similar peaks at ~1000 Ma, ~1500 Ma, and ~1850 Ma (fig. 5). Both samples contain zircons within the ~500 to 650 Ma age range (table 1) and Silurian and Ordovician age peaks are apparent in both samples (fig. 5). However, the nature of these populations and the number of zircons within these populations differ between the eastern and western Gile Mountain Formation samples.

Sample 4 (obtained from graded beds in the western part of the CVS) contains abundant zircons ranging in age from ~405 to 420 Ma (table 1). Among the 60

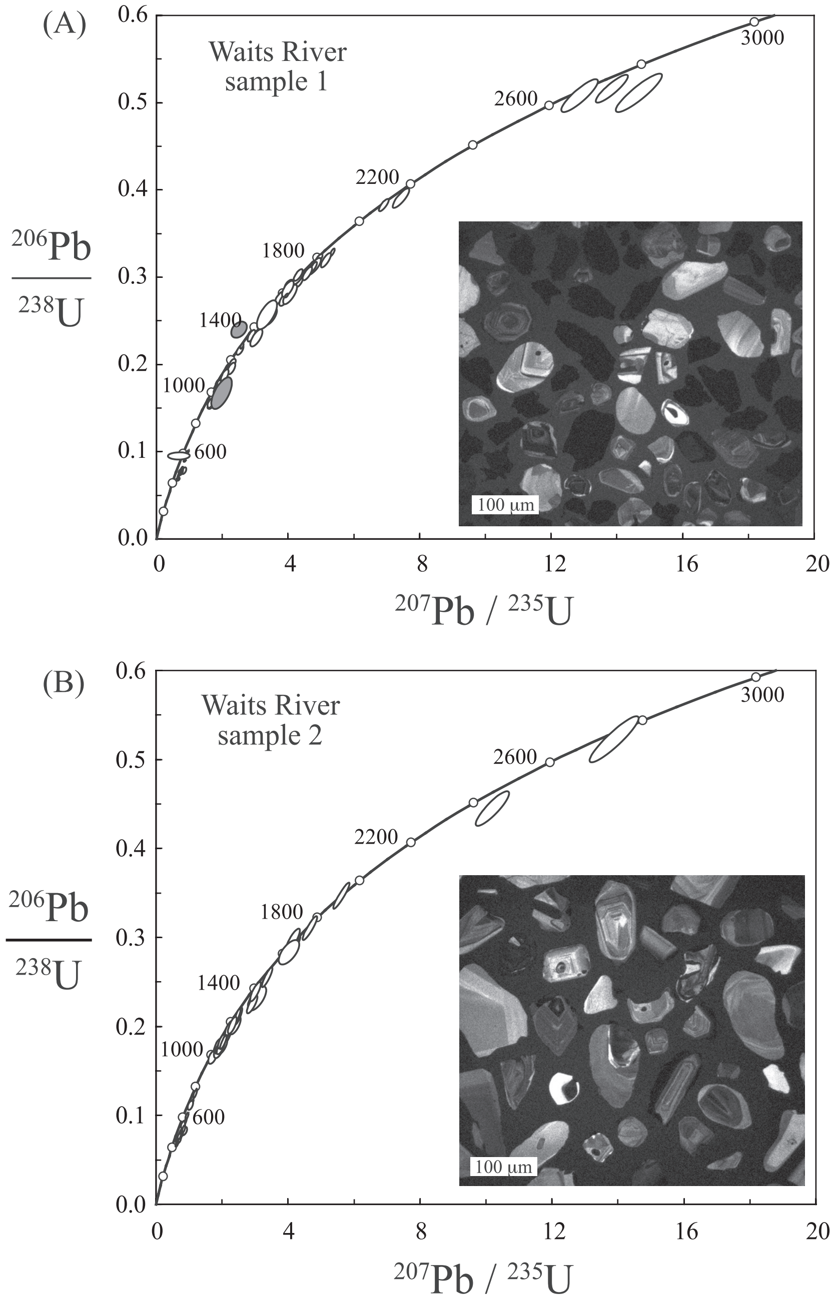


Fig. 6. Cathodoluminescent (CL) images of typical zircons and concordia diagrams showing results of U-Pb SHRIMP analyses of zircons from each sample. Concordant and slightly discordant (white ellipses) and rejected discordant (gray ellipses) analyses are indicated. CL images of zircons show oscillatory and sector zoning in rounded detrital magmatic grains. (A) Sample 1 from the Waits River Formation. (B) Sample 2 from the Waits River Formation.

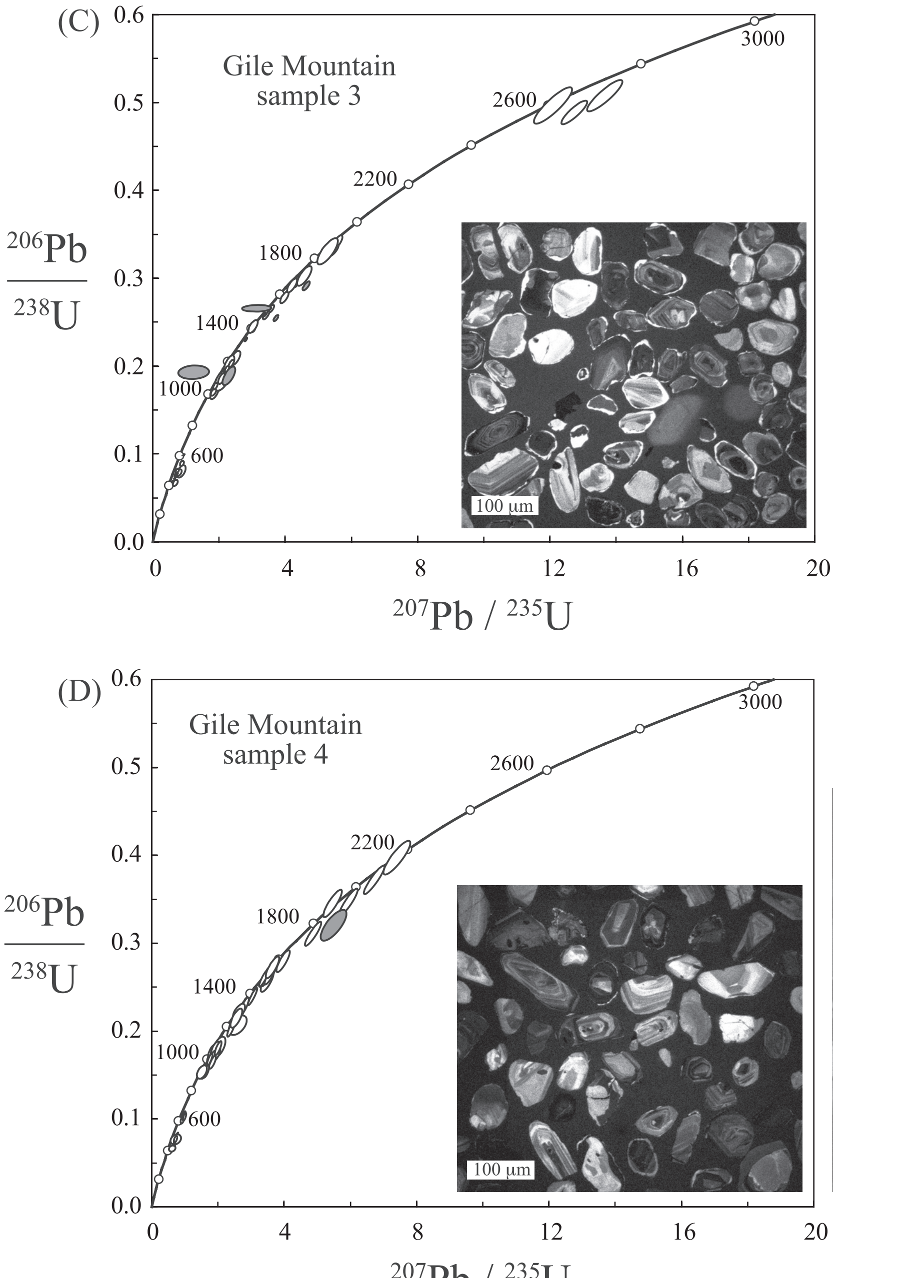
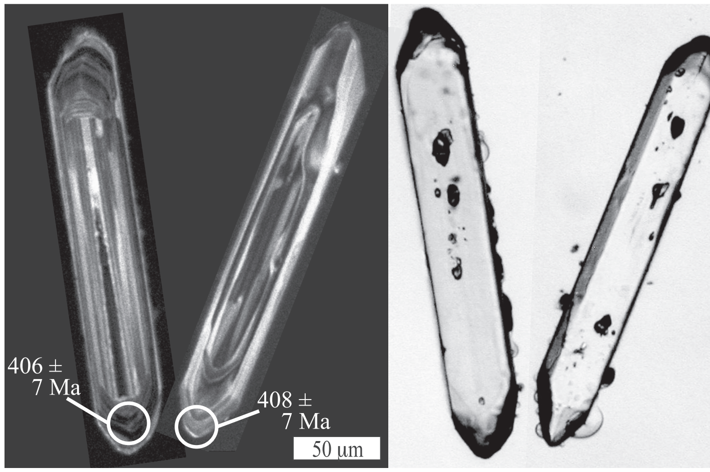


Fig. 6 (continued). (C) Sample 3 from the Gile Mountain Formation. Metamorphic rims are apparent on all grains. (D) Sample 4 from the Gile Mountain Formation.

randomly selected grains, 13 analyses fall within this age range. Zircons of this age are typically elongate and commonly euhedral, likely representing a single population of volcanic zircons (see above). Furthermore, 12 of 16 handpicked grains also fall within this range. These results indicate that a large percentage of the zircons within this



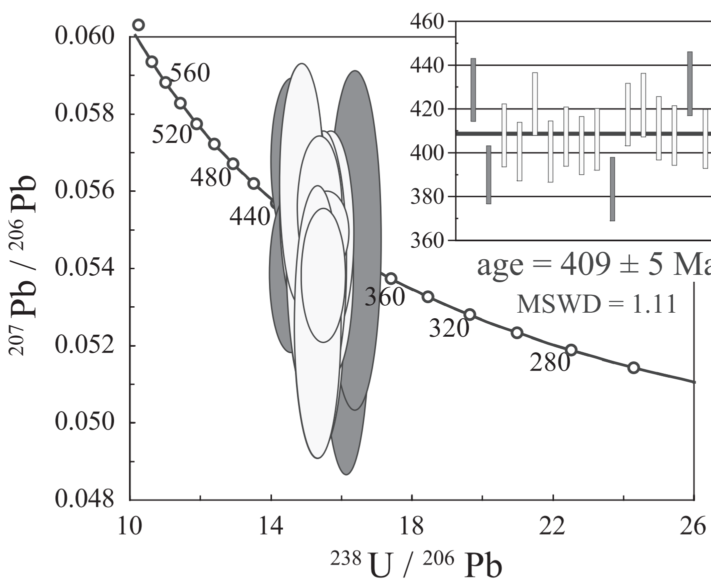


Fig. 7. CL and transmitted light images of representative zircons and a Tera-Wasserburg Concordia plot (with an inset showing the weighted average of $^{206}Pb/^{238}U$ ages) of 16 analyses of hand-picked zircons from sample 4 from the Gile Mountain Formation. Of these analyses, 12 were chosen to represent a single age population (white ellipses) and four were rejected (gray ellipses).

sample are of the same age population (~409 Ma, see above; fig. 7). Conversely, zircons from the eastern sample (sample 3) typically lack the elongate euhedral morphology and only three grains yielded ages within the ~405 to 420 Ma range, suggesting different provenances for a portion of the zircons within the eastern and western samples. Although the Meso- and Neoproterozoic ages within both samples likely suggest a similar provenance, the source of the ~409 Ma zircons in sample 4 to the west was apparently not accessible to the eastern part of the basin during the deposition of sediments from sample 3. These data suggest either, 1) that these sediments are not time-correlative across the basin, or 2) sediments to the west had local access to zircons not deposited in the eastern portion of the basin.

Provenance

Despite the >1000 km length of the CVGT (for example, Hibbard and others, 2006) and extensive exposures within the basin, the source(s) of these sediments remains ambiguous (for example, Hatch, 1988a; Rankin and others, 2007). Any tectonic reconstruction involving the development of the CVGT would be strongly dependent on the sources of sediment in the basin. In order to investigate the provenance of these sediments, age populations present in each sample are examined individually (fig. 5).

Precambrian zircons.—Every sample contains a significant population (>50%) of Precambrian age zircons (figs. 4 and 5). Numerous potential sources of Precambrian zircons exist in close proximity to the CVGT both west (for example, McLelland and Chiarenzelli, 1990; Ratcliffe and others, 1991; Tucker and Gower, 1994; Rivers, 1997; Walsh and others, 2004) and east (for example, van Staal and others, 1996; Aleinikoff and others, 1995; Cawood and others, 2001; Walsh and others, 2007) of the basin. However, reworking of early Paleozoic sediments that contained detrital zircons in this age range must also be considered. Thus, the presence of Precambrian age zircons in these samples is not a good indicator of provenance for these sediments.

Cambrian zircons.—Each sample contains at least one zircon of Cambrian age. Among these ages, all but one is within analytical error of the age range identified in the Barnard Volcanic Member (496-462 Ma, Ratcliffe and others, 1997) or the Shelburne Falls arc (485-470 Ma, Karabinos and others, 1998 and references therein) to the west of the CVGT making these igneous rocks a potential source. One zircon, identified in sample 2 from the Waits River Formation, yielded an age of 517 $\pm$ 8 Ma (table 1), older than the currently accepted age range in the Shelburne Falls arc. However, this age is not replicated and is statistically insignificant.

Ordovician zircons.—Each sample collected from the CVGT contains numerous (~10%) zircons of Ordovician age (fig. 5B). This is expected, as pervasive igneous activity of this age has been identified along the length of the northern Appalachians both east and west of the CVGT (fig. 8). Ordovician plutonic and volcanic rocks identified in New England include, but are not limited to, the Ammonoosuc Volcanics (469-458 Ma; Moench and Aleinikoff, 2003), the Bronson Hill arc (454-442 Ma; Tucker and Robinson, 1990), the Shelburne Falls arc (485-470 Ma; Karabinos and others, 1998 and references therein), the Brookfield plutonic series (454-438 Ma; Sevigny and Hanson, 1995), the Candlewood Granite and associated migmatitic rocks (443-445 Ma; Walsh and others, 2004), the Killingworth arc (460-456 Ma; Aleinikoff and others, 2007), the Middletown complex (459-449 Ma; Aleinikoff and others, 2007), and the Oliverian plutonic suite (456-435 Ma; Aleinikoff and others, 2002; Moench and Aleinikoff, 2003).

Numerous Ordovician igneous rocks are also identified to the north in Canada including, but not limited to, the Ascot complex (462-460; David and others, 1993; Tremblay and others, 2000), the Victoria arc (473-454 Ma; Zagorevski and others, 2007), the Penobscot arc (513-486 Ma; Zagorevski and others, 2007) and the back-arc Exploits subzone (468-454 Ma; Valverde-Vaquero and others, 2006). Thus, zircons with ages from 513 to 435 Ma were available as detritus in the CVGT. The pervasive geographic nature of these potential sources precludes the distinction between eastern and western sources (fig. 8).

Silurian zircons.—Silurian age zircons occur in all four samples. Many potential distal sources for these zircons exist in the northern Appalachians. A series of plutons including the East Inlet, Ayer, and Newburyport plutons (Lyons and others, 1997 and references therein) east of the CVGT are known to contain Silurian zircons. The

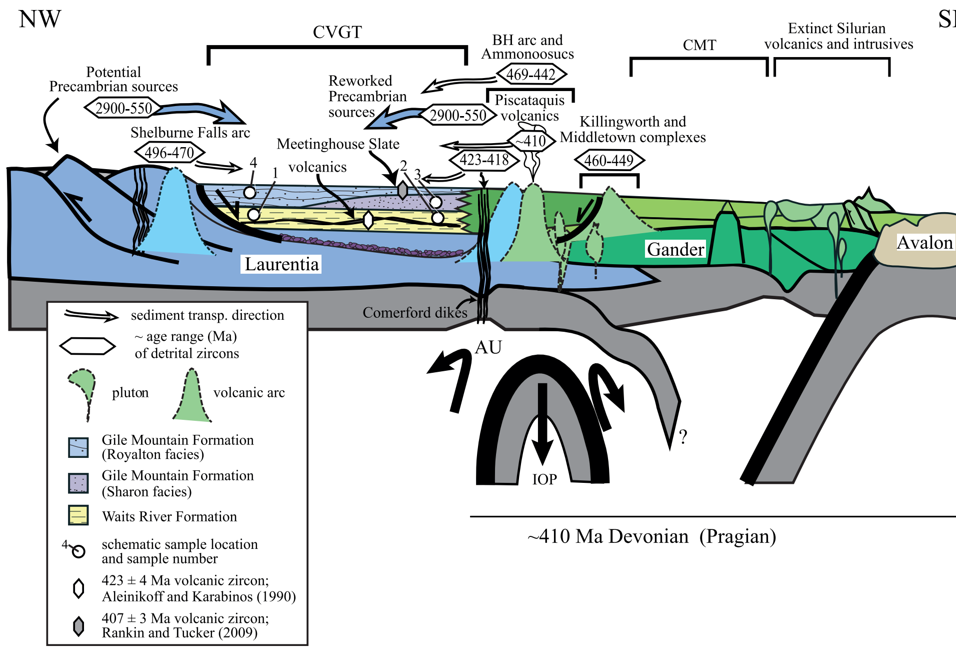


Fig. 8. Schematic NW-SE (present coordinates) cross section for the Early Devonian showing potential sources for detrital zircons in sediments of the Connecticut Valley-Gaspé trough (CVGT). The Central Maine trough (CMT) and extinct Silurian volcanic and intrusive rocks are shown to the east of the CVGT. The Laurentian-derived Shelburne Falls and Bronson Hill (BH) arcs as well as the Gander-derived Killingworth and Middletown complexes were no longer active while the Piscataquis magmatic belt was active. Continued convergence of Gander and Laurentia led to the descent of the doubly-subducting Iapetan oceanic plate (IOP), causing asthenospheric upwelling (AU), intrusion of the Comerford dikes, and extension of Laurentian crust. Normal faulting led to the development of the CVGT involving both eastern and western sources of sediment throughout the history of deposition. Modified from Aleinikoff and others (2007), and Wintsch and others (2007).

Coastal volcanic belt (~442-420 Ma; Bradley and others, 2000; Barr and others, 2002; Moench and Aleinikoff, 2003; Van Wagoner and Dadd, 2003) east of the Central Maine trough contains abundant Silurian zircons but sediments from so far to the east are unlikely in the CVGT (fig. 8). Distal dated sources to the west of the CVGT include the Dell Trondhjemite in northwestern Massachusetts (434 ± 8 Ma; Karabinos and Aleinikoff, 1991), and the Pumpkin Ground orthogneiss in southwestern Connecticut (428 ± 2 Ma; Sevigny and Hanson, 1993).

More proximal sources include a series of igneous rocks with remarkably consistent ages (~418-423; see Aleinikoff and Karabinos, 1990; Moench and others, 1995; Lyons and others, 1997; Rankin and others, 2007) that appear to be closely associated with sedimentation in the CVGT. These include discontinuous interbedded volcanic units within the Waits River and Gile Mountain Formations (Armstrong and others, 1997; Ratcliffe, 2000b; Ratcliffe and Armstrong, 2001). To date, only one rock in this belt of volcanic rocks has yielded an age—zircons collected from a metafelsite in Springfield, Vermont yielded a U-Pb TIMS age of 423 ± 4 Ma (Aleinikoff and Karabinos, 1990). Sills and dikes identified on either side of the basin may be related to these volcanics, but the intrusive rocks do not cross the basin's limits and therefore the age of the intrusions may place a lower limit on the deposition of some of the CVGT rocks. In central Vermont to the west of the basin beneath the Shaw Mountain Formation, a felsic gneiss interpreted as a volcanic layer or a possible Silurian sill

(Aleinikoff and Karabinos, 1990) is interlayered within the Barnard Volcanic Member of the Missisquoi Formation (Doll and others, 1961). All other rocks in the Barnard belt have yielded older Cambrian to Ordovician ages (Ratcliffe and others, 1997; Karabinos and others, 1998). The felsic gneiss was dated at 418 ±1 Ma (Aleinikoff and Karabinos, 1990). A monzodiorite dike from the Braintree complex also intrudes the pre-Silurian rocks in central Vermont (Ratcliffe and Aleinikoff, 2000) and yielded a similar age of 419 ± 1 Ma (Black and others, 2004). The Charlemont Mafic Intrusive Suite in northwestern Massachusetts is undated but cuts the Dell Trondhjemite (434 ± 8 Ma; Kim and Jacobi, 1996) and is geochemically indistinguishable from the volcanic units interbedded within the Waits River and Gile Mountain Formations (Karabinos and Hepburn, 2001). East of the CVGT a series of tuffs and dikes in northern New Hampshire, Maine and Québec have ages of ~418 Ma, including rocks from the Frontenac and Perry Mountain Formations (Moench and others, 1995; Lyons and others, 1997). The Comerford Intrusive Suite in northeastern Vermont (419 ± 1 Ma; Rankin and others, 2007) is also possibly related to these volcanic units (Rankin and others, 2007). Given the close proximity of these sills and dikes to the CVGT and the apparent relationship to the volcanic units within the basin, detrital zircons in the ~420 Ma age range were likely derived locally both east and west of the basin (fig. 8), and likely correspond to the timing of early basin development at around 420 Ma (Rankin and others, 2007).

Devonian zircons.—A strong peak in zircon ages at about 409 Ma is present in sample 4 of the Gile Mountain Formation from the western part of the CVGT (sample 4; fig. 5B). A continuous belt of igneous rocks east of the CVGT running from western New Hampshire through Maine (Piscataquis magmatic belt of Bradley, 1983; Bradley and others, 2000; Bradley and Tucker, 2002; Hibbard and others, 2006; Rankin and others, 2007; see fig. 1) contains a series of plutons with remarkably consistent ages of 405 to 409 Ma (Bradley and others, 2000). Tucker and others (1998) reported zircon ages of 408 ± 2 Ma in the Sprout Brook ash from Cherry Valley in upstate New York, which Bradley and Tucker (2002) related to the Piscataquis magmatic belt indicating significant extrusive igneous activity. This volcanic activity may also be responsible for the interbedded rhyolites with ages of ~407 to 409 Ma identified within both the Gile Mountain and Littleton Formations in northeastern Vermont and northwestern New Hampshire (Rankin and Tucker, 2000, 2009). The euhedral, elongate, doubly-terminated habit and the presence of inclusion tubes in the hand-picked zircons from sample 4 (weighted average of 409 ± 5 Ma, see fig. 7) suggest a proximal volcanic origin and may represent direct deposition of volcanic ash into this siliciclastic sediment. Volcanic activity from the Piscataquis belt just east of the CVGT is a likely source of these zircons (fig. 8).

Age of Deposition

The depositional age of the Waits River and Gile Mountain Formations can be constrained by the age of the youngest detrital zircon population, which is the maximum age of the host sediment. Individual zircon ages obtained in the Waits River Formation are as young as 418 ± 7 Ma (table 1, sample 2) in the east and 415 ± 2 Ma (table 1, sample 1) in the west. While these are single grain analyses and do not represent statistically significant age populations, they are older (within error) of sample 4 from the Gile Mountain Formation and are consistent with the stratigraphic topping criteria in the area of sample 4 which show that the Gile Mountain Formation is stratigraphically above the Waits River Formation (Fisher and Karabinos, 1980). Acknowledging the uncertainty in the dataset, we argue that the data loosely constrain a maximum age of deposition of the youngest sediments in the Waits River Formation at ~415 Ma.

This interpretation of an Early Devonian depositional age for the Waits River Formation bears on the age of a felsic rock near Springfield, Vermont. A conventional $^{207}Pb/^{206}Pb$ zircon age of 423 ± 4 Ma was obtained from a metafelsite associated with the Waits River Formation (Aleinikoff and Karabinos, 1990; Hueber and others, 1990), although the interpretation of the felsite and its age is still disputed. Aleinikoff and Karabinos (1990) maintain the sample came from a crosscutting dike requiring sediments at this locality to be older than 423 Ma, but left open the possibility that the sampled rock was a layer because of unclear cross-cutting relationships. Walsh and others (1996a, 1996b) and Armstrong and others (1997) did not observe crosscutting relationships in this outcrop and inferred that the age is from an interbedded volcanic layer, hence yielding the age of the host sediments. In light of the younger ages obtained in this study, we suggest that the felsite layer is an interbedded volcanic rock and that its age directly dates the deposition of the Waits River Formation at this stratigraphic level (fig. 3). Future work is still needed to test the $^{207}Pb/^{206}Pb$ zircon age of 423 ± 4 Ma and to date the metasedimentary rocks at Springfield. Until then, the current data set contains a range in ages from about 423 Ma obtained near Springfield, to a maximum age of 415 Ma just south of Montpelier, which establishes a Wenlockian to Lochkovian age for sediments of the Waits River Formation (fig. 9).

Sample 4 from the Gile Mountain Formation in the Townshend-Brownington syncline in the western part of the basin contains detrital zircons as young as 403 ± 7 Ma. The crystal morphology of these zircons is similar to the elongate, euhedral, doubly-terminated hand-picked grains from this sample (409 ± 5 Ma, see fig. 7) interpreted to be ash fall related to the Piscataquis magmatic belt (see above). All detrital grains having apparent ages <409 Ma are within analytical error of 409 Ma and likely belong to this volcanic population. Thus, a maximum age of ~409 Ma is established for strata of the Gile Mountain Formation in the western part of the basin. A minimum age of deposition may also be implied by the well-established Acadian deformational front that approaches the CVGT at ~407 Ma (Bradley and others, 2000; Bradley and Tucker, 2002). This is corroborated by thermal modeling and Late Devonian $^{40}Ar/^{39}Ar$ cooling ages of amphibole (Spear and Harrison, 1989; McWilliams and others, 2006) requiring immediate burial and metamorphism of these rocks after ~409 Ma. Given this maximum age of deposition and supporting geologic evidence, we support a model for deposition of these sediments during the Pragian.

We suggest that this depositional age is probably younger than the age of sediments collected at sample site 3 of the Gile Mountain Formation to the east, but accept that the lack of a statistically robust detrital zircon age population from sample 3 means that this interpretation is not entirely supported by the geochronologic data. The ~409 Ma age obtained from a weighted average of 12 hand-picked zircons in the western sample (sample 4) suggests that zircons are likely derived from the Piscataquis magmatic belt east of the CVGT (Bradley and others, 2000). Furthermore, ages of 13 of the 60 randomly selected zircons in sample 4 overlap in error with the weighted average of the hand-picked grains (table 1) indicating the magmatic belt likely supplied a significant portion of zircons to the sediments at sample site 4. However, only two of the 60 randomly selected zircons in Gile Mountain Formation sediments in the eastern part of the basin (sample 3) yielded ages that overlap in error with the hand-picked zircons from sample 4 (fig. 5B, table 1). The paucity of zircons as young as ~409 Ma in the eastern sample coupled with the proximal extrusion of Piscataquis volcanic zircons (~405-409 Ma, Bradley and others, 2000) suggest that the sediments at sample site 3 of the Gile Mountain Formation may have been deposited and buried before the Piscataquis magmatic belt was shedding sediment into the basin. Alterna-

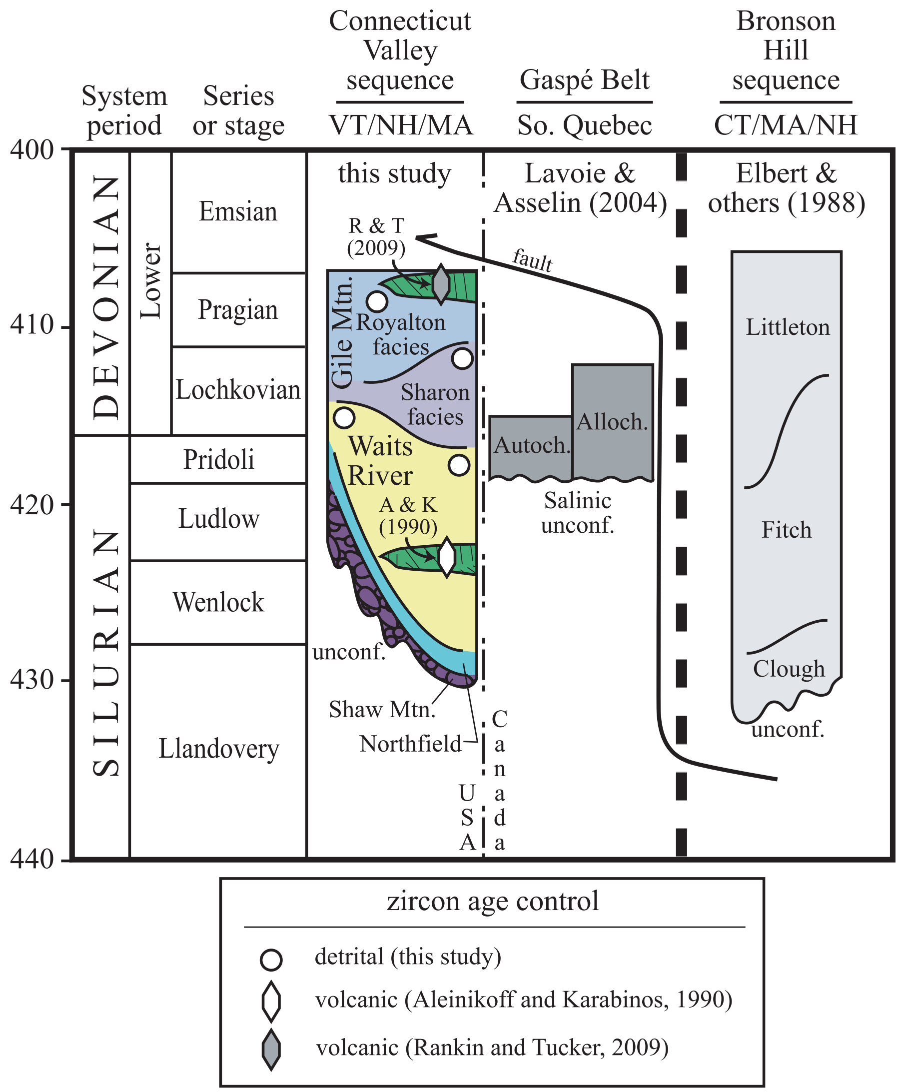


Fig. 9. Correlation chart showing the Silurian-Devonian stratigraphic section of the Connecticut Valley-Gaspé trough including the Connecticut Valley sequence (this study), the along strike autochthonous and allochthonous rocks in southern Québec (Lavoie and Asselin, 2004) and the generally correlative Bronson Hill sequence (Elbert and others, 1988). Zircon age control for the CVS includes the youngest detrital zircon age obtained from each sample (circles), and conventional U-Pb zircon ages from a metafelsite in the Waits River Formation (white diamond symbol, Aleinikoff and Karabinos, 1990) and a metarhyolite in the Meetinghouse Slate (gray diamond symbol, Rankin and Tucker, 2009).

tively, if the rocks at sample site 3 are younger, then the ~409 Ma source rocks would have had to entirely bypass sample site 3, which seems unlikely. The youngest age of 411 ± 8 Ma in the eastern sample is a single-grain zircon analysis while the age from the western sample site is a weighted average of 409 ± 5 Ma. These ages overlap in error, and do not adequately constrain the relative depositional ages at the two sample sites, but possibly bracket deposition of the sediments at sample site 3 between ~411 and ~409 Ma (fig. 9).

Stratigraphic Speculations

Sampling sites in metasedimentary rocks of the Gile Mountain Formation in the eastern and western parts of the basin yield different relative probability distributions of detrital zircon ages, suggesting that these rocks may differ in provenance and are not correlative across the CVS (see above). In addition, a facies change is present (Hatch, 1988a) in which sediments to the east are characterized by micaceous, feldspathic, quartzite interbedded with phyllite whereas sediments to the west consist of rhythmically bedded quartzites (turbidites). Finally, the dominant population of zircons dated at ~409 ± 5 Ma in the western sample (sample 4) suggests that the sediments to the west are possibly younger than those to the east. Given these differences, we divide rocks traditionally mapped as the Gile Mountain Formation. The eastern sediments dominated by quartzite with interbedded phyllite are informally referred to hereon as the Sharon facies whereas the western sediments of rhythmically bedded quartzite are informally referred to as the Royalton facies (figs. 3B and 9).

Late Silurian

In Late Silurian time, deposition began with sediments of the Shaw Mountain Formation. Discontinuous quartz-pebble conglomerate and rusty-weathering feldspathic grit, likely representing recycled sediments, found at the base of the CVS make up the Shaw Mountain Formation and are interpreted to mark an unconformity (Doll and others, 1961; Walsh and others, 1996a; Armstrong and others, 1997; Ratcliffe and Armstrong, 2001). Possible Llandoverian fossils in the Shaw Mountain Formation may provide a lower age limit for deposition of the conglomerates (Boucot and Thompson, 1963; Boucot and Drapeau, 1968; Doll, 1984), but their occurrence is at odds with dated intrusive rocks at around 418 to 419 Ma that do not cross the basal unconformity. Pridolian and Ludlovian fossils (Boucot and Drapeau, 1968) are in better agreement with constraints placed by the dated intrusive rocks beneath the unconformity, and led Ratcliffe and Aleinikoff (2000) to suggest that the Shaw Mountain Formation was deposited transgressively onto the western side of the CVGT. Occurrence of Llandoverian fossils in the Clough quartzite on the eastern side of the CVGT in the Bronson Hill sequence (Boucot and others, 1958; Boucot and Thompson, 1963) suggests that the Clough may in part be older than the Shaw Mountain (Ratcliffe and Aleinikoff, 2000), even though both may mark the base of the CVGT (Hatch, 1988a; Tremblay and Pinet, 2005; fig. 9). The overlying Northfield Formation consists of gray carbonaceous phyllite with minor sandy lenses and graded beds (for example, Armstrong and others, 1997; Ratcliffe, 2000b; Ratcliffe and Armstrong, 2001). These sediments were likely deposited in a continental slope-like environment. A precise age for the Northfield Formation has not yet been determined.

Deposition of the Waits River Formation followed deposition of the Northfield Formation (Doll and others, 1961; Walsh and others, 2010; fig. 3). The Waits River Formation is dominated by gray phyllite with interbedded marble (Doll and others, 1961; Armstrong and others, 1997; Hatch, 1988a), plus local quartzite and volcanic rocks (fig. 2). One felsic rock dated at 423 ± 4 Ma (Aleinikoff and Karabinos, 1990; Hueber and others, 1990) requires deposition of these sediments near Springfield, in late Wenlockian times. Both eastern and western sources for sediment of the Waits River Formation are suggested by detrital zircon ages presented above, supporting an intracontinental extensional back-arc setting for deposition. The youngest single-grain zircon analysis from the Waits River Formation yielded a Lockhovian age of 415 ± 2 Ma, however, this age alone may not be statistically significant.

Early Devonian

The detrital zircon ages presented above suggest that the western Royalton and eastern Sharon facies of the Gile Mountain Formation probably should not be correlated across the basin and that the Sharon facies might be older than the Royalton facies. Hence, quartz-rich sands interbedded with silts and shales of the Sharon facies were probably deposited on strata of the Waits River Formation in the eastern part of the CVS. While poor single-grain statistics and analytical uncertainty preclude firm constraints, deposition of the Sharon facies may have continued into the Pragian, as evidenced by the age of the youngest zircon identified in the Sharon facies (411 Ma $\pm$ 8 Ma; see fig. 8). The absence of a quartzite-dominated sediment underlying the Royalton facies to the west suggests that deposition of sediments of the Sharon facies may not have been laterally continuous across the basin, thereby supporting the model by Hatch (1988a; fig. 3B). Euhedral, elongate zircons identified in the Royalton facies are likely derived from the Piscataquis magmatic belt, suggesting that the pulse of volcanic activity to the east from $\sim$405 to 409 Ma (Bradley and others, 2000) contributed zircons to the turbidites with deposition of the Royalton facies continuing until at least 409 $\pm$ 5 Ma (fig. 3B). Occurrence of Emsian and Pragian fossils in the Littleton Formation of the Bronson Hill sequence (Boucot and Arndt, 1960; Boucot and Rumble, 1980) suggests that the Littleton Formation is likely correlative with the Royalton facies of the Gile Mountain Formation (fig. 9), comprising the stratigraphic top of the CVGT.

A new U-Pb zircon TIMS age of 407 $\pm$ 3 Ma by Rankin and Tucker (2009) from a metarhyolite in the Meetinghouse Slate Member of the Gile Mountain Formation clarifies the stratigraphic relationship of the Meetinghouse to the remainder of the CVS, and confirms that the Meetinghouse corresponds to the top of the Gile Mountain Formation. If the Meetinghouse Slate is indeed the stratigraphic top of the Gile Mountain Formation in the eastern part of the basin, then it must be younger than the underlying sediments of the Sharon facies ($\sim$411 Ma; see fig. 3B) and thus may correlate with the Royalton facies to the west with a depositional age $\sim$409 Ma. The relationship between the Meetinghouse and the Royalton facies is not observable in central Vermont because of complex Acadian folding, nor has it been tested in northern Vermont by modern structural analysis and detailed mapping (fig. 2). In northern Vermont, future work is needed to test the stratigraphic continuity between the Meetinghouse Slate and the Royalton facies of the Gile Mountain Formation.

TECTONIC SPECULATIONS

Ages of detrital zircons from the Waits River and Gile Mountain Formations bear directly on the overall tectonic setting and evolution of the CVGT. The double subduction zone model of the Iapetan oceanic plate (for example, van Staal and others, 1998; Valverde-Vaquero and others, 2006; Aleinikoff and others, 2007; van Staal, 2007; Wintsch and others, 2007) provides context to understand the data presented above. This model suggests the Bronson Hill arc and the Killingworth and Middletown complexes formed on opposite sides of the Iapetus oceanic plate above opposite-dipping subduction zones (see fig. 17 of Aleinikoff and others, 2007), and were juxtaposed during the Salinic orogeny as Gander collided with Laurentia (fig. 8; for example, Dunning and others, 1990; van Staal, 2005; van Staal, 2007).

Tectonic models invoking the collision of the Gander block with Laurentia in the Silurian (fig. 8) are in apparent conflict with Silurian extension documented by many workers in the northern Appalachians (Lavoie, 1992; Malo and Kirkwood, 1995; Malo, 2001; Tremblay and Pinet, 2005; Rankin and others, 2007). Several lines of evidence exist for this Silurian extension in western New England including trace element compositions (Hepburn, 1991; Slack and others, 2001) and geochemical signatures of mafic igneous rocks consistent with intrusion in a back-arc extensional environment (Rankin and others, 2007). Numerous faults are also interpreted to reflect extension during Silurian times (for example, Tremblay and Castonguay, 2002). Tremblay and Pinet (2005) noted that extensional features can be traced along the length of the northwestern boundary of the CVGT from the Burgess Branch fault zone in Vermont (Kim and others, 1999) to the Shickshock Sud fault zone in the Gaspé Peninsula (Malo and others, 2001). Regionally in Québec, these faults are thought to have developed along with syn-sedimentary normal faults (Castonguay and Tremblay, 2003; Sacks and others, 2004) during the Salinic event (Bourque and others, 2000; Malo, 2001), an event named after the phrase "Salinic disturbance" first recognized by Boucot (1962).

These apparently contradictory interpretations can be reconciled when viewed in the context of promontories and embayments. Since the advent of plate tectonics, it has been recognized that continent-continent collisions occur first at promontories (Wilson, 1966). Palinspastic reconstructions of the eastern continental margin of Laurentia identify the St. Lawrence promontory as having been a conspicuous feature during the opening of the Iapetus Ocean (fig. 1; Thomas, 1977; Thomas, 2006). The Québec embayment just south of the St. Lawrence promontory follows the western boundary of the CVGT from Gaspé bay south to south-central Connecticut (for example, Hibbard and others, 2006). A model involving diachronous collision was proposed by Rankin and others (2007) to help explain Silurian extension and intrusion of the Comerford intrusive suite in northern Vermont and New Hampshire. Tremblay and Pinet (2005) proposed a similar model to explain the formation not only of the CVGT but also of the adjacent Central Maine Trough (see fig. 8). Indeed, predominantly sinistral transpression during the Salinic event identified in Newfoundland (for example, van Staal, 2007 and references therein) could have led to extension south of the St. Lawrence promontory (Rankin and others, 2007).

In addition, the double-subduction model predicts the foundering and eventual sinking of the Iapetan oceanic plate into the mantle (fig. 8). Descent of this oceanic plate could have led to lithospheric delamination and asthenospheric upwelling, causing elevated heat flow at the lithosphere-asthenosphere boundary. Such a thermal perturbation may have caused extension of the lithosphere and eventual stretching of the crust which produced normal faulting and the topographic relief required for the formation of the thick Silurian and Early Devonian deposits in the CVGT (fig. 8). Thus, we favor a tectonic model involving a combination of lithospheric delamination and diachronous collision of Gander and Laurentia, which likely led to extension of the Laurentian crust and sedimentation in the CVGT during the Silurian. Detrital zircon data presented here favor both eastern and western provenances during deposition of Silurian through Devonian sediments of the CVGT (fig. 8). Furthermore, the lithologic boundary between the Gile Mountain and Waits River Formations, representing a shift from argillaceous and calcareous silt, siliceous limestone and mud to quartzo-feldspathic sand and argillite (fig. 3) has profound tectonic implications when presented in the context of these detrital zircon ages. If the quartzite-dominated facies of the Gile Mountain Formation (Sharon facies) represents proximal foreland deposits, then a shift in the nature of the basin is identified, from an intercontinental rift environment (Tremblay and Pinet, 2005; Rankin and others, 2007) to a foreland-style basin (Bradley and others, 2000; Bradley and Tucker, 2002). Moreover, the timing of this shift is loosely constrained by detrital zircon ages collected above and below the lithologic boundary. While the data lack statistical certainty, maximum ages of the sediments fall between $\sim$415 $\pm$ 2 Ma and $\sim$411 $\pm$ 8 Ma suggesting this shift took place in late Silurian to early Devonian times. Slack and others (1993) noted that the change from carbonate-dominated to largely siliciclastic sedimentation was coincident with extrusion of the Standing Pond volcanic rocks. Our interpretations provide a possible mechanism for the change in sedimentation and suggest the onset of the termination of rifting.

Following this shift, distal turbidites of the Royalton were deposited in the western part of the basin at $\sim$409 Ma, perhaps at the same time sediments of the Meetinghouse

Slate were deposited in the eastern part of the CVS and the Littleton Formation was deposited on the Bronson Hill sequence (figs. 3B and 9; Moench and others, 1995; Lyons and others, 1997; Rankin and others, 2007). The Royalton facies and the Meetinghouse Slate are dominated by fine-grained silt, mud and turbidites and were probably deposited in a deeper-water environment. The well-documented transgressive event in the CVGT to the north in Québec corresponds to the end of the T2 event and onset of the third regressive cycle (R3 of Bourque and others, 1995; Malo, 2001; Lavoie and Asselin, 2004). This relative sea-level high-stand would have led to a deeper-water environment in the basin. This shift to a deeper-water environment may have resulted from lithospheric flexure and basin subsidence caused by the doubly-thickened crust of the Acadian wedge just east of the basin (Bradley and others, 2000; McWilliams and others, 2007). If Acadian metamorphism of CVGT sediments took place immediately after deposition of the Royalton facies at ~409 Ma (see above), then the time constraint of this shift agrees well with the suggested arrival of the Acadian deformational front at ~407 Ma (Bradley and others, 2000; Bradley and Tucker, 2002).

CONCLUSIONS

Detrital zircon ages obtained from quartz-rich sand of the Waits River and Gile Mountain Formations constrain the provenance and age of these sediments, suggesting tectonic models for the development of the CVGT. Late Silurian normal faulting attributed to a combination of back-arc extension, the diachronous collision of Gander with Laurentia and lithospheric delamination produced the topographic relief required for sedimentation in the basin. Sediments of the Shaw Mountain and Northfield Formations were deposited unconformably on Ordovician basement in a continental slope-like environment. Silt and shale with interbedded carbonate and minor quartz-rich sand of the Waits River Formation were deposited upon the Northfield Formation in a similar, slope-like depositional environment from sometime before ~423 Ma until at least 415 ± 2 Ma. Deposition of the Sharon facies of the Gile Mountain Formation followed at ~411 ± 8 Ma. Occurrence of the predominantly quartzo-feldspathic sand of the Sharon facies suggest that the source of these sediments likely was from the approaching Acadian deformational front leading to a shift in the style of the basin from an intercontinental rift environment to a foreland-style basin. Finally, a transgressive event coupled with basin subsidence led to deposition of the finer-grained sediments of the Royalton facies and Meetinghouse Slate at ~409 ± 5 Ma. Subsequent to deposition, immediate loading and metamorphism of the entire CVGT took place during the Acadian orogeny. The most likely scenario for this event involves emplacement of westward-migrating thrust sheets from the Bronson Hill and Central Maine terranes over the CVGT, possibly due to the collision of the Avalonian block with the eastern margin of the Gander block.

ACKNOWLEDGMENTS

The authors would like to thank J. Aleinikoff, P. Karabinos, D. Rankin, J. Slack, and C. van Staal for reviews on earlier drafts that greatly improved this paper. Thanks to S. Dee for sample preparation, J. Schieber for help with SEM imaging, J. Aleinikoff for advice on analysis, and F. Mazdab for help using the SHRIMP-RG. This research was partially supported by the Geological Society of America Grants in Aid of Research, the New England Intercollegiate Geologic Conference Marland Pratt Billings and Katharine Fowler-Billings Fund for Research in New England Geology, the United States Geological Survey, the National Science Foundation grant EAR-0510293 to Wintsch and Dorais, and by the Indiana University Department of Geological Sciences.

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