INTRODUCTION

The Oliverian Magma Series is a suite of tonalitic to granitic igneous rocks exposed in the cores of mantled domes within the Bronson Hill anticlinorium (Fig. 1; Billings, 1937; Thompson et al., 1968; Naylor, 1969; Robinson et al., 1991). The rocks range in age from 454 ± 3 Ma to 442 ± 2 Ma, and are immediately overlain on all sides by Ordovician cover, the Ammonoosuc Volcanics (453 ± 2 Ma) and Partridge Formation (449 ± 3 Ma; all ages are from Tucker and Robinson, 1990). These cover rocks include mafic and felsic metavolcanic rocks, which have clear geochemical affinities with island arcs (Hollacher, 1985; Schumacher, 1988; Hingston, 1992), as well as metapelites. The magma series is usually interpreted as the intrusive rocks of an island arc that formed prior to and during the Ordovician Taconian orogeny, that were deformed and metamorphosed during the Devonian Acadian orogeny (Robinson and Hall, 1980; Tucker and Robinson, 1990; Ratcliffe et al., 1998).

In the traditional view (Billings, 1937; Thompson et al., 1968; Robinson and Hall, 1980; Lyons et al., 1996), Oliverian Magma Series gneisses are autochthonous and mantled by a (para)autochthonous volcanic and sedimentary cover. The contact between the gneisses and the overlying Ammonoosuc Volcanics has been viewed as intrusive (Billings, 1937; Zartman and Leo, 1985; Lyons et al., 1996), conformable (Naylor, 1969), or unconformable (Robinson et al., 1979). Inasmuch as the Ammonoosuc Volcanics are unquestionably extrusive, and rarely more than ~1000 m thick (Robinson et al., 1991), these interpretations imply shallow intrusion depths (~1 km or less) for the magma series. Our new pressure-temperature (P-T) estimates obtained for Oliverian Magma Series crystallization conditions, however, indicate emplacement at 30–35 km, and thus challenge these views. In addition, the apparent absence of significant Acadian metamorphism in the gneisses contrasts with ubiquitous Acadian-age, sillimanite-grade metamorphism in the cover, that were deformed and metamorphosed during the Devonian Acadian orogeny (Robinson and Hall, 1980; Tucker and Robinson, 1990; Ratcliffe et al., 1998).

PETROLOGY AND PRESSURE-TEMPERATURE ESTIMATES

We examined eight domes in New Hampshire. In two of them, the Alstead and Keene domes (Fig. 1), Oliverian Magma Series rocks contain garnet gneisses (442–454 Ma) in the cores of domes in southwestern New Hampshire have an igneous mineralogy that crystallized at pressures (P) of 9–11 kbar and temperatures (T) of 650–775 °C, whereas the cover (Ammonoosuc Volcanics) has the same formation age (453 ± 2 Ma) yet is clearly extrusive. A significant crustal section, ~30 km thick, must have originally separated the two units, a recognition that demands tectonic reinterpretation of this classic orogen. Acadian age (ca. 400 Ma) metamorphism at P ~4–6 kbar, T ≥ 625 °C is well documented in the cover, but the absence of expected diffusional reequilibration in Oliverian garnets indicates that they never exceeded ~550 °C after formation. Juxtaposition of the Oliverian Magma Series gneisses and their cover must have occurred after the cover had cooled below 550 °C, and was likely via either (neo-)Acadian or Alleghanian thrusting.

Figure 1. Generalized geologic map of central New England after Tucker and Robinson (1990), showing geographic disposition of Oliverian Magma Series gneisses and major lithotectonic units. BM and GMM = Berkshire and Green Mountain massifs (Proterozoic), TA = Taconian allochthons (Ordovician), KD = Keene dome, and AD = Alstead dome. Cover to domes consists of Ordovician Ammonoosuc Volcanics and Partridge Formation, and overlying Silurian-Devonian units (Clough, Fitch, and Littleton Formations). Small box shows location of inset; inset shows sample locations.
(Grt), biotite (Bt), epidote (Ep), and either hornblende (Hbl) or muscovite (Ms), in addition to quartz (Qtz), plagioclase (Pl), magnetite (Mt) and K-feldspar (Kfs). All minerals are texturally and compositionally igneous (Fig. 2, A–C). Plagioclase is normally zoned (An35–24) and most abundant. Hornblende is rare, subhedral and embayed, and occurs with Pl. All other minerals tend to occur in <1- to 5-mm-diameter pockets, and as foliations between Pl-rich bands. Epidote is coarse grained and euhedral, occasionally has allanite cores, and is restricted to mineral clusters with Hbl and/or Bt (Fig. 2A); this occurrence contrasts with typical metamorphic Ep in metaigneous rocks that nucleates within calcic Pl. Garnet is euhedral to subhedral, and sometimes is found as inclusions in Pt, but more often occurs in segregations with Bt, Qtz, Ms (in Hbl-absent rocks), Mt, and Kfs (Fig. 2A). These textures follow a typical igneous crystallization sequence: early growth of Pl + Hbl + Grt was followed by later growth of Ep + Bt + Grt, and finally Qtz + Kfs ± Ms. The occurrence of the latter phases into pockets and stringers likely reflects segregation and smearing of the melt in a differential stress field after initial crystallization of Pl and Hbl. Similar assemblages and textures were described by Barth and Ehlig (1988) and Paterson et al. (1998) for other middle to deep-seated plutons.

Garnet compositions and zoning patterns indicate a deep crustal igneous origin. Garnets have high XCa (0.2–0.35), complex internal zoning, and broad core-rim increases in Mn and Fe/(Fe + Mg) (Fig. 2, B and C). Much of the complex zoning reflects anatistic changes in Mn + Fe vs. Ca, but internal variability in Mn/(Mn + Fe + Mg) and Fe/(Fe + Mg) indicates that Ca variations alone do not control the distribution of Fe, Mg, and Mn. Garnet adjacent to matrix Bt exhibits no local increase in Fe or Fe/(Fe + Mg), as expected if diffusional exchange has occurred. These compositions and internal zoning contrast with typical metamorphic Grt from the cover, which has low and flat Ca, flat Fe/(Fe + Mg) and Mn profiles in cores, and a small increase or decrease in Mn at the rim (Fig. 2, D and E; Spear et al., 1995). The zoning patterns in cover Grt reflect extensive diffusional homogenization during peak Acadian metamorphism (ca. 400 Ma), followed by retrograde growth and/or resorption of Grt during cooling (Chamberlain, 1986; Spear et al., 1995). In contrast, the zoning patterns in Oliverian Magma Series Grt reflect crystallization from a melt and an absence of diffusional modification. As feldspar crystallizes, XMn in the melt increases, causing an increase in XMn in the trace amounts of Grt formed (e.g., Barth and Ehlig, 1988). Local variations in melt composition because of melt migration and segregation would cause large variable changes in Mn, Fe, and Ca, and could be recorded as complex Grt zoning. The strong gradients in all components imply an absence of significant diffusional modification after crystallization.

Mineral compositions1 allow quantification of intrusion P–T conditions (Fig. 3). Magmatic temperatures of 650–775 °C are obtained with the Grt-Bt and Grt-Hbl thermometers, using Grt cores and isolated matrix Bt and Hbl. These compositional pairings are justified by textures (crystallization of Grt with Bt and after Hbl) and chemical trends (increasing Fe/[Fe + Mg] toward Grt rims). Essentially identical results are obtained with Hbl-Pl and Zr saturation thermometers. The inferred intrusion depths are more surprising: Grt-Pl and Al-in-Hbl barometers indicate P = 9–11 kbar and P = 8–10 kbar at T = 700 °C. These pressures contrast with extrusive textures in the coeval cover, and imply that ca. 450 Ma, the magma series intruded 30–35 km below their present cover. The similarity of P–T results using equilibria that involve minerals that grew at different times is consistent with chemical equilibration and in situ crystallization. Garnet-biotite rim temperatures are 500–650 °C, and could reflect either Grt growth during a later event (Acadian?), or final crystallization of the latest-stage magmatic fluids.

The strong compositional variations within magma series Grt also implies rapid postcrystallization cooling and no subsequent reheating above ≈550–600 °C. Otherwise zoning would be smooth and diffusional profiles would exist adjacent to Bt, as is observed in metapelite garnets a few tens of meters above the magma series gneisses. P–T conditions (Fig. 3) for the cover are –650 °C and 4–6 kbar (Keene dome; this study; Schumacher et al., 1989) and ~625 °C and 4 kbar (Alstead dome; Spear et al., 1995). The Keene cover also has textural evidence for prograde Ms and Bt dehydration-melting reactions, whereas the magma series gneisses do not. Because the cover underwent Acadian metamorphism at T ≥ 625 °C, the magma series and cover must have remained separate ca. 400 Ma.

**DISCUSSION**

The Oliverian Magma Series is geographically associated with the coeval Ammonoosuc Volcanics. The volcanic rocks were clearly extrusive,

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1GSA Data Repository item 9970, Mineral compositions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or www.geosociety.org/pubs/drprint.htm.
with relict pillows and vesicles and evidence for hydrothermal alteration by
seawater (Spear, 1980; Schumacher, 1988). The trace element chemistry of
the magma series and Ammonoosuc Volcanics is similar and indicates an
island-arc origin (Schumacher, 1988; Hingston, 1992). Given statements of
previous workers that the magma series intrudes the Ammonoosuc Volcanics
(Billings, 1937; Zartman and Leo, 1985; Lyons et al., 1996), a shallow origin
for the magma series as the intrusive counterpart of the arc volcanic rocks
seems obvious. How can we explain the petrologic results? Like others
(Naylor, 1969; Robinson et al., 1979; Schumacher, 1988; Tucker and Robin-
son, 1990), we find no field evidence for intrusion of plutonic Oliverian
Magma Series into extrusive Ammonoosuc Volcanics, a conclusion that de-
pends critically on stratigraphic assignments. The magma series core
gneisses underlie and intrude a suite of mafic and felsic metaigneous rocks
(now amphibolites and felsic gneisses), which are immediately overlain by
the clearly extrusive, mafic metavolcanic rocks of the Ammonoosuc Vol-
canics. Controversy over the Ammonoosuc–Oliverian Magma Series contact
has centered on the intervening mafic-felsic suite. Some workers assign it to
the Ammonoosuc Volcanics, implying that the magma series intruded shal-
low volcanic rocks, whereas others assign the suite to the magma series. Our
examination of most of the domes in western New Hampshire and descrip-
tions of domes in Massachusetts (P. Robinson, 1990, personal commun.)

Figure 3. Pressure-temperature (P-T) results for Alstead (AD) and Keene (KD)
domes. Fine stipple pattern shows Grt core results for Oliverian Magma Series
rocks that contain hornblende (Hbl), garnet (Grt), biotite (Bt), and plagioclase
(Pl), by using Grt-Bt, Grt-Hbl, and Grt-Hbl-Pl-quartz (Qtz) thermobarometry
(Graham and Powell, 1984; Ferry and Spear, 1978; Berman, 1990; Kohn and
Spear, 1990); alternative Grt-Bt calibration, and Hbl-Pl and Zr saturation, and
Al-in-Hbl thermobarometers (Watson and Harrison, 1983; Zr data from
Hingston, 1992; Holland and Blundy, 1994; Anderson and Smith, 1995) yield
similar results. Coarse stipple pattern shows Grt rim results for Oliverian
Magma Series rocks (including Grt-Pl-muscovite barometry; Powell and
Holland, 1988). Open boxes show results for cover rocks (Spear et al., 1995;
this study), which were metamor-
phosed during Acadian orogeny at high T, low P. Schematic phase rela-
tions for calc-alkaline magmas are after Clemens and Wall (1981) and Kenah
and Hollister (1983).

Figure 4. Illustration of our preferred interpretation of Paleozoic events in
central New England. A: Intrusion of Oliverian magmas at ~30 km depth
and extrusion of Ammonoosuc Volcanics forms Bronson Hill arc (BHA),
which collides with North America (NA) ca. 450 Ma to produce Taconian
orogeny (Robinson and Hall, 1980; Ratcliffe et al., 1998). B: Post-Taconian
erosion raises Oliverian Magma Series (MS) gneisses to 10–20 km depth
as thick Silurian sediments accumulate in adjacent Merrimack basin.
Acadian deformation then buries Ammonoosuc Volcanics to depth of
~20 km. C: Later thrusting juxtaposes now-cool Ammonoosuc Volcanics
with Oliverian Magma Series gneisses. TA = Taconic allochthons.
indicate no intrusive relationships between the mafic-felsic suite and the intrusive Ammonoosuc Volcanics, and no evidence that the mafic-felsic suite was originally extrusive. Therefore, we interpret the primary Oliverian Magma Series–Ammonoosuc contact to be above the mafic-felsic suite (Robinson et al., 1979; Schumacher, 1988), and the sharp contact to be a major structure. This reconciles all observations: the magma series intruded the mafic-felsic suite, but at a depth of ~30–35 km, whereas the Ammonoosuc Volcanics were extruded at the surface. Later events juxtaposed the units.

What is the nature of the present Oliverian Magma Series–Ammonoosuc contact, and where are the 30 km of crust that once separated these two units? In two previous interpretations, the contact is depositional, and either conformable (Naylor, 1969) or unconformable (Robinson et al., 1979). Tucker and Robinson (1990) measured crystallization ages of 453 ± 2 Ma for both the upper Ammonoosuc Volcanics and the magma series gneisses of the Keene dome, allowing at most ~3 m.y. for removal of 30 km of crust when age uncertainties are considered. They also postulated that the contact may be a normal fault. However, rapid exhumation seems implausible. There are no thick sedimentary rocks of Late Ordovician age, and interpretations invoking pre-Acadian juxtaposition cannot explain the P-T discontinuity between the Oliverian Magma Series and its cover, or the lack of evidence for high-T low-P metamorphism of the magma series.

We believe that the Oliverian Magma Series and cover were never juxtaposed until at least the Acadian orogeny (ca. 400 Ma) and possibly much later, after the cover had already cooled. Some magma series gneisses have taposed until at least the Acadian orogeny (ca. 400 Ma) and possibly even Alleghanian (250–300 Ma). In our scenario (Fig. 4), the Oliverian Magma Series intruded at a depth of ~30 km ca. 450 Ma (Fig. 4A), exhumed to 10–20 km depth during the Silurian (to help produce thick Silurian sequences), and then simply resided there until 400 Ma or later (Fig. 4B). During the (neo) Acadian or the Alleghanian, the Ammonoosuc Volcanics, now buried to a similar depth, were thrust onto the Oliverian Magma Series gneisses (Fig. 4C).

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REFERENCES CITED

Barth, A. F., and Ellings, P. L., 1988, Geochemistry and petrogenesis of the marginal zone of the Mount Lowe intrusion, central San Gabriel Mountains, California: Contributions to Mineralogy and Petrology, v. 100, p. 192–204.
Hollander, K. T., 1985, Geochemistry of metamorphosed volcanic rocks in the Middle Ordovician Partridge Formation, and amphibole dehydration reactions in the high-grade metamorphosed zones of central Massachusetts [Ph.D. thesis]: Amherst, University of Massachusetts, 275 p.

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