Bedrock geology of the Paleozoic rocks of western New Haven quadrangle, Connecticut

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ABSTRACT

The Paleozoic rocks underlying the western third of the New Haven Quadrangle, Connecticut, are mapped at a scale of 1:24,000. This area of ∼41.5 km\(^2\), previously mapped only in reconnaissance, contains polymetamorphic argillites and mafic rocks. The northern portion of the mapped area contains the pelitic Wepawaug schist, whereas the southern portion is underlain by the pelitic Savin Schist. Between them lies the Maltby Lakes Complex (MLC) that contains newly identified fault slivers of variably metamorphosed mafic phyllites and amphibolites. Metamorphic foliations in both the MLC and the Savin Schist are truncated by a swarm of basalt dikes: the Allingtown porphyry, which is itself commonly schistose and locally mylonitic. Previous interpretations held that these rocks constitute a conformable, northwest-topping stratigraphic sequence. In contrast, we propose that Ordovician(? oceanic rocks of the MLC were variably metamorphosed and faulted against the Ordovician(? Savin Schist. These were intruded by a swarm of stitching Allingtown dikes. This package of rocks was then faulted against Siluro-Devonian(?) Wepawaug forearc sediments. Existing thermochronology indicates a Devonian age of the subsequent regional metamorphism, overprinted by low-grade Permian fabrics associated with dextral transpression and final terrane assembly.

1. Introduction

1.1. Geologic setting

The Orange-Milford Belt (OMB) of mafic and argillitic rocks lies at the southeastern margin of Connecticut’s Western Highlands (Rodgers, 1985). It is bound on the west by the East Derby Shear Zone (EDSZ), a greenschist facies ductile fault (Hatch & Stanley, 1973; Wathen et al., 2015). West of this fault are high-grade metasediments and orthogneisses associated with the Laurentian margin (Crowley, 1968; Sevigny & Hanson, 1993, 1995). The eastern boundary of the OMB is marked by the nonconformably overlying arkoses of the Hartford basin. Just south of the New Haven quadrangle the Eastern Border Fault of the Hartford basin places anatectic rocks of peri-Gondwanan affinity (Aleinikoff \textit{et al.}, 2007) against the OMB. The tectonic affinities of the rocks of the OMB are presently unknown. Along-strike structural relationships suggest the OMB may correlate with the Connecticut Valley Trough (CVT) in Vermont. In the absence of independent constraints, some units in New Haven quadrangle are given tentative age assignments based on this correlation, as discussed below (Ages of Map Units).

The OMB was regionally metamorphosed during Devonian Acadian orogenesis (Growdon, Kunk, Wintsch, & Walsh, 2013). Fabrics formed during this event are now exposed in a field gradient that increases in metamorphic intensity from east to west (Ague, 1994a, 1994b; Fritts, 1965a, 1965b). The relatively low grade of regional metamorphism in eastern exposures allowed the rocks there to escape the thorough Devonian overprinting that visited the western OMB. Our new mapping of the eastern OMB in New Haven quadrangle (Main Map) reveals slivers of high-grade mafic rocks enclosed within chlorite grade fabrics. These tectonic slivers preserve evidence of early Paleozoic metamorphism otherwise undocumented in south-central Connecticut.

1.2. Previous work

Previous work in the New Haven quadrangle has involved only reconnaissance mapping. Percival (1842) described a ‘Chloritic formation’ at the

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Thermochronologic investigation of the OMB in the Ansonia quadrangle by $^{40}$Ar/$^{39}$Ar methods reveals muscovites with Devonian cooling ages preserved in microlithons between overprinting folia of muscovites with Permian crystallization ages (Growdon et al., 2013), ages that are consistent with deformation broadly attributable to the Acadian and Alleghanian orogenies, respectively. Fabrics conformable with these are identified in the New Haven quadrangle, as discussed below.

2. Methods

2.1. Map area

The map area includes approximately the western third of New Haven quadrangle in south-central Connecticut (EPSG 2234). The eastern boundary of the study area, defined as the Triassic nonconformity, is geologically, not geographically, controlled and is therefore somewhat irregular. Coordinates for the map area clockwise from the northwest corner of the New Haven quadrangle are as follows:

| Latitude | Longitude |
|----------|-----------|
| 41° 22′ 30.0″ | N 73° 0′ 0.0″ W |
| 41° 22′ 30.0″ | N 72° 58′ 40.5″ W |
| 41° 20′ 46.0″ | N 72° 58′ 40.5″ W |
| 41° 16′ 13.0″ | N 72° 56′ 46.0″ W |
| 41° 15′ 0.0″ | N 72° 56′ 46.0″ W |
| 41° 15′ 0.0″ | N 72° 0′ 0.0″ W |

2.2. Field methods

Outcrops were located using a Samsung SCH-I400 cellular phone operating the GPS Essentials freeware application. Locations were recorded in geographical coordinates using the 1983 North American datum. Of several devices employed, including two dedicated Garmin units, the Samsung provided the most accurate and precise global positioning system (GPS) coordinates (generally within 9 m), likely because the urban/suburban terrain and gentle topography allowed the Samsung device to use both satellite and Verizon Mobile networks in obtaining its position. In rare circumstances when GPS was not available, location was obtained by pace-and-compass and noted on the field sheet.

Structures were measured with a standard azimuthal Brunton compass. All field data were recorded in pencil in field notebooks. Contacts and lithologies were recorded on 1:3000, 1:6000, or 1:12,000 field sheets, depending on outcrop density and local structural complexity. Analytical data acquired by a variety of methods, including X-ray fluorescence, X-ray diffraction, and electron probe microanalysis, have contributed to the characterization and discrimination of the map units presented here (Deasy, Bish, & Wintsch, 2009).
2.3. Map compilation

Basemap data (topography, transportation, hydrography, and geographic names) were downloaded as .zip files from www.ct.gov/deep/gisdata and were processed in Esri ArcGIS 10.1. Field data were compiled in Microsoft Excel and uploaded to ArcGIS 10.1 for representation. Map symbols follow the Federal Geographic Data Committee Cartographic Standard for Geologic Map Symbolization (FGDC, 2006). The map was prepared with the Connecticut State Plane FIPS (US Feet) projection. Many representation layers were exported from ArcGIS as .ai files, and the final map was assembled in Adobe Illustrator CS6. Stereonets in Figure 1 were prepared with Stereonet for Windows (Allmendinger, 2004). Stereonets in Figure 2 were prepared using WindRose for Matlab (Pereira, 2015). Color photographs (Plates 1–13) were taken with a Nikon D80 digital camera and annotated in Adobe Illustrator CS6.

3. Results

3.1. Identification of map units

The immediate goal of mapping was the identification and discrimination of Paleozoic units. The eastern boundary of the map area was therefore set as the non-conformity between the Paleozoic units and the overlying Triassic New Haven arkose (Trnh, Plate 1). Units are distinguished by mineralogy, textures, and structures, and locally also by mineral chemistry and whole-rock chemical compositions. While outcrop scale heterogeneities cannot be differentiated at the map scale, structurally and/or mineralogically distinct rock types that occur at many outcrop localities within a more continuous unit are given separate unit designations. For example, in the MLC, weakly foliated lozenges of metagabbro (Omg) are mapped separately from the epidote-pod mylonite (Omc).

These results broadly conform with previous studies in recognizing four major lithologic groups. These are:

(1) the Wepawaug Schist of metasediments, dominated by phyllite (SDws, Plates 2 and 3) with minor impure carbonate (SDwm) and foliated feldspathic metawackes (SDww);
(2) the Allingtown Porphyry [Sap (Plates 4–6)], a massive to mylonitic plagioclase basalt porphyry; and
(3) the MLC of greenstones [Omc (Plates 1, 7, 8), Omt], amphibolites [Omg (Plate 8), Omm (Plate 9), Oma (Plate 10)], and serpentinite [Omc5 (Plate 11)];

(4) the two units within the Savin Schist include a foliated mélangé [Osm (Plate 12)] and a strongly foliated and commonly well-lineated muscovite-chlorite schist with minor quartzite [Oss (Plate 13)].

Finally, the youngest bedrock unit is a Jurassic basalt dike (Jd) which cuts through the MLC near the Silver Brook Fault (SBF) (Philpotts & Martello, 1986).

3.2. Ages of map units

No independent constraints presently exist for the depositional age of the Wepawaug Schist. The Wepawaug Schist may correlate with the Waits River Formation of the CVT in Vermont, which was deposited in the late Silurian to early Devonian (McWilliams, Walsh, & Wintsch, 2010). The metamorphic muscovites in the Wepawaug Schist in Ansonia quadrangle have late Devonian cooling ages with Permian overprinting folia, recording deformation during the Acadian and Alleghanian orogenies, respectively (Growdon et al., 2013). The ages of the rocks of the MLC are constrained by a single whole-rock Rb-Sr age of 460 Ma (Armstrong et al., 1970) that at best records the time of high-grade fabric formation. The Allingtown dike swarm correlates both structurally and geochemically with the late Silurian Comerford Intrusive Suite which intrudes the CVT (Deasy & Wintsch, 2015; Rankin et al., 2007). No constraints on the depositional age of the Savin Schist, or on the timing of fabric development in that unit, are currently available. We therefore defer to previous workers’ assignment of this unit as Ordovician (e.g. Rodgers, 1985).

3.3. Metamorphism

The Paleozoic rocks mapped in New Haven quadrangle are all metamorphosed to at least lower greenschist facies conditions and most are moderately to strongly foliated and/or lineated. All members of the Wepawaug Schist are strongly foliated (Figure 1(A)). Contiguous muscovite folia define the fabric of the phyllite (SDws) and impure marble (SDwm). The coexistence of K-feldspar and chlorite in the metawacke (SDww) confirms metamorphism below the biotite isograd.

The appearance of the epidote-pod chlorite schist (Omc) in the field is dominated by lenses and knots of very fine-grained epidote wrapped by contiguous folia of chlorite and minor amphibole (Plate 7), suggesting deformation at upper greenschist facies conditions. The chlorite fabric envelops lozenges a few centimeters to several meters across that preserve a metagabbroic fabric of coarse-grained, poorly lineated amphibole porphyroclasts (Omg, Plate 8). The coarse-grained, well-lineated fabric of the gneissic amphibolite (Oma) persists as lozenges enveloped by
amphibole mylonite (Omm, Plate 9). Both the coarse-grained fabric and the mylonitic fabric are defined by well-lineated amphibole. The coarse grains of the gneissic amphibolite (Oma) have actinolitic compositions and the fine grains in the mylonite (Omm) have hornblende compositions, indicating deformation took place under prograde metamorphic conditions, from greenschist through amphibolite facies (Deasy et al., 2015).

The relict metamorphic clasts preserved in the foliated mélange unit of the Savin Schist (Osm, Plate 12) contain fabrics defined by chlorite and white mica, suggesting lower greenschist facies crystallization. The muscovite folia that envelop the clasts were similarly developed at lower greenschist facies conditions. The coexistence of K-feldspar and chlorite in the phyllitic and psammitic rocks in the structurally lower Savin Schist (Oss) confirm metamorphism and foliation development below the biotite isograd.

3.4. Structure

3.4.1. Paleozoic metamorphic fabrics

The oldest fabrics in these rocks include the foliations in the metagabbro (Omg), in the amphibolites (Oma, Omm), and the fabrics preserved in the clasts of both mélangé units (Omsc, Osm). The fabric-forming amphiboles in the mylonite (Omm) show the highest (amphibolite facies) grade of metamorphism in the map area (Deasy et al., 2014), and so this fabric and...
that of its gneissic inclusions (Oma) must predate those of all other rocks. The 015-striking mylonitic fabric in the greenschist facies chlorite schist (Omc) suggests roughly east–west shortening and north-south extension during fabric development (Figure 1(B)). Consistent with this, the fractures in brecciated epidote pods suggest north–south extension (Plate 7). Poles to folded foliations in the amphibole mylonite (Omm), serpentine (Omcs), and foliated micaceous mélange (Osm) define a plane (Figure 1(C)), suggesting these units were folded together. The mean axis of these folds as well as mineral lineation orientations suggest roughly the same stress field as would produce the fabric of the chlorite mylonite (Omc, Figure 1(B)) and is evidence that the structures developed together.

Northern and western exposures of the cross-cutting Allingtown dike swarm (Sap) are strongly transposed into the enclosing epidote-chlorite mylonite (Omc). Highly attenuated plagioclase phenocrysts, some with aspect ratios >20:1, suggest the dikes intruded prior to and experienced the same east–west shortening and north–south extension. These relationships suggest that this folding occurred under greenschist facies conditions and probably during the Acadian orogeny (Growdon et al., 2013).

The fabrics in the MLC described above are utterly distinct from those in the rocks to the south. The main body of the Allingtown dike swarm (Sap) was apparently undeformed during metamorphism (Plate 10), excepting very minor and localized shear bands. In southern exposures of the dikes and throughout the Savin Schist (Oss), a northwest-dipping fabric dominates (Figure 1(D)). A shallowly plunging, northeast-bearing intersection lineation becomes most prominent in exposures near Long Island Sound (Plate 13).

3.4.2. Mesozoic structure

The nonconformity where the Triassic New Haven arkose overlies the Paleozoic rocks of the OMB is exposed in only one place in the New Haven quadrangle (Plate 1). Few clasts in the basal conglomerate are locally derived. Rather, the quartz-, feldspar-, and muscovite-dominated sediment load was sourced from the granitic Bronson Hill highlands to the east (Blevins-Walker et al., 2001), which requires a net westward dip of the depositional surface. The present orientation of this surface, although irregular, dips ~35° to the east (Plate 1, inset). The exposure of the contemporaneous surface in Roaring Brook, some
30 km to the north (41°36′28.9″N 72°55′39.6″W; Fritts, 1963b), shares the same orientation, indicating a regional >35° eastward rotation about a subhorizontal axis striking ~010. Many of the now subvertical structures in the Paleozoic rocks have thus been steepened or overturned to the east by this rotation.

3.4.3. Faults
In areas of abundant outcrop many more faults than previously recognized have been identified. These include both ductile faults marked by metamorphic fabrics, and brittle faults marked by breccia where exposed. Evidence for these faults is described below, with ductile faults first.

3.4.3.1. Indian River Fault. This fault is recognized on the basis of a locally well-exposed brecciated (and refoliated) schists including the calcitic serpentinite of the MLC (Omc, Plate 11) and the mélange of the Savin Schist (Osm, Plate 12). The angular to round clasts in each mélange unit preserve mineralogies which indicate the two units experienced independent metamorphic histories prior to brecciation and refoliation (Deasy et al., 2016). The IRF marks a profound lithologic contact between the mafic/ultramafic MLC rocks and the quartzo-feldspathic Savin Schist. Dikes of the Allington porphyry intrude rocks on either side of the IRF and truncate the fabric of the refoliated matrix. Thus, the juxtaposition of the MLC and the Savin Schist must predate the inferred Silurian emplacement of the dikes.

3.4.3.2. Orange Hills Fault. The boundary between the epidote-pod unit (Omc) and the amphibole mylonite...
(Omm) must be a fault because it places the greenschist facies Omc against the amphibolite facies Omm. It is not exposed in the New Haven quadrangle because for most of its length it is cut out by the Western Border Fault (WBF). However, it is inferred to underlie the glacial sediments in the extreme SW margin of the quadrangle where it strikes SW to join the same boundary in the Ansonia quadrangle.

3.4.3.3. Silver Brook Fault.

This fault is recognized on the basis of several features. First, the cleavages in the Wepawaug schist trend to ∼030, whereas those in the MLC south of the fault trend 015. The fault also places the higher metamorphic grade of the epidote-chlorite-amphibole schist (Omc) with MORB-like compositions (Deasy et al., 2014) on the SE against the lower grade pelitic Wepawaug phyllite (SDws) on the NW. As the fault is approached from the NW, quartz veins in the Wepawaug phyllites become isoclinally folded, attenuated, and dismembered with aspect ratios of these veins approaching 100:1 (Plate 3). On the southern margin of the fault epidote in the chlorite schist (Omc) forms porphyroclasts, and the schist becomes pinstriped and locally mylonitic (Plate 7). The SBF thus juxtaposes strongly contrasting rock units with distinct metamorphic fabrics and distinct
metamorphic grades and is marked by an increase in ductile strain along the contact. The absence of Allingtown dikes (Sap) cutting across the fault suggests that motion post-dates the emplacement of these dikes.

3.4.4. Mesozoic faults and brittle deformation

3.4.4.1. Western Border Fault. This fault marks the western extent of much of the Hartford Basin and cuts out the Triassic nonconformity in the northern third of New Haven quadrangle. The fault is marked by breccias and can be identified by offset of metamorphic fabrics for the length of 4 km. Although lost under glacial cover in the southern third, it is inferred to transect the entire quadrangle.

3.4.4.2. Mixville Fault. This fault trends 015 through Ansonia quadrangle to the west (Fritts, 1965a). Its projects into the northwestern-most New Haven quadrangle where north–south trending outcrops of brecciated phyllite cemented with vuggy quartz are present.

3.4.4.3. Cove River Fault. This fault is exposed in breccias and by the offset in the Jurassic diabase dike (Jd) just south of Rte. 243. Its possible convergence with the Zak Hill Fault to the north or the WBF to the south is obscured by glacial cover.

Plate 5. Sheeted dikes of the Allingtown dike swarm (Sap). One of many intrusive contacts (dashed line) exposed within the main body of the Allingtown dike swarm (Sap). Inset stereogram shows poles to undeformed contacts of newer Sap dikes intruding older Sap dikes. Half dikes and dikes with two chill margins are both exposed. Half dikes do not show systematic opening direction. Contacts with eastward-coarsening porphyry (hollow circles, n = 10) are slightly more abundant than westward-coarsening contacts (filled circles, n = 8).

Plate 6. Allingtown dike (Sap) cutting the Savin Schist (Oss). The weakly foliated dike truncates (dashed line) a coarse-grained muscovite-chlorite-quartz metamorphic fabric in the schist (Sn-1, dotted line). Later deformation has folded and refoliated the schist (Sn, solid lines) and penetratively chloritized the dike.

Plate 7. Epidote-pod chlorite schist and mylonite (Omc). Fine-grained aggregates of epidote (Ep) form boudins in a fine-grained chlorite fabric. Low-weathering extensional fractures (dashed lines) in epidote pods are filled with carbonate or, uncommonly, asbestiform amphibole. The epidote pods are thought to have originated as veins, disaggregated by shearing. Also present in this image are coarse-grained, subspherical epidote porphyroblast aggregates (arrows).

Plate 8. Metagabbroic inclusions (Omg) in chlorite mylonite (Omc). The chlorite schist (Omc) includes 0.01–5 m inclusions of a massive, coarse-grained metaggabro (Omg) containing saussuritized plagioclase and uralitized clinopyroxene. Lens cap is 53 mm in diameter.
3.4.4.4. Zak Hill Fault. This fault lies subparallel to and between the Mixville Fault and the WBF. It is revealed by a ∼10° offset in the orientation of fabric elements in the Wepawaug schist across a strike-parallel valley.

3.4.4.5. Ray Bishop’s Pond Fault. This fault trends ENE and extends beyond the mapped area, possibly truncating West Rock sill at its southern boundary. This fault is interpreted to explain the drop in topography to the north and east of Bishop’s pond, and the offset in the trend of the Buttress dike (Jd).

3.4.5. Joints

Orientations of late, through-going joints are given in windrose stereonets in Figure 2. Structural domains are divided by faults and lithologic contacts. Fracturing in the Wepawaug Schist is dominated by the fissility of the phyllite (SDws) along its folia (Figure 2(A)). Another prominent joint set dips steeply to the southwest. Jointing in the chlorite schist and mylonite (Omc) suggests east–west shortening that may be contemporaneous with the Ray Bishop’s Pond Fault (Figure 2(B,C)). The MLC exposed east of the WBF was deforming brittly in the Permian, forming the K-feldspar veins that are common near the Maltby Lakes (Deasy et al., 2015). Many later generations of joints record Permian and Mesozoic deformation (Figure 2(D)). Prominent southwest-dipping joints in the Allingtown dike swarm and Savin Schist suggest deformation under stress conditions similar to those that induced jointing in the Wepawaug Schist to the north (Figure 2(E,F)).

Plate 9. Epidote-amphibole gneiss (Oma) and mylonite (Omm). The Maltby Lakes Complex preserves lozenges of amphibolite facies, prograde mafic gneiss (Oma), and mylonite (Omm). The image above shows the partial replacement of the gneissic actinolite-plagioclase texture by the epidote-actinolitic hornblende mylonite.

Plate 10. Allingtown dike (Sap) cutting coarse-grained fabric in mafic gneiss (Oma). In this image a massive porphyritic dike (Sap) cuts the strongly lineated gneiss (Oma) at a high angle (dashed line). This locality was apparently untouched by later deformation that elsewhere folded units of the Maltby Lakes Complex and foliated the Allingtown dikes (e.g. Plate 4).

Plate 11. Calcitic serpentinite (Omc). This cut surface exposes the mélangé texture of this unit, with subangular-to-round, massive-to-foliated clasts of serpentinite (S) in a foliated serpentine, calcite, and magnetite matrix. The foliation runs parallel to that of the dominant foliation in the adjacent micaceous mélangé (Osm, Plate 12).

Plate 12. Savin Schist micaceous mélangé (Osm). This unit is characterized by the presence of angular clasts of fine-grained chlorite schist (C) in a coarse-grained, foliated muscovite-chlorite matrix. Folded ribbons of disaggregated quartz veins are also characteristic. The dominant fabric, subvertical in this image, is truncated by intrusions of the Allingtown dike swarm.
4. Conclusions

The geologic history of the OMB is far more complicated than has been previously recognized. The textures of the gabbroic (Omg) and gneissic (Oma) units preserved in the MLC preclude the possibility that those units originated as extrusive volcanic rocks. The metamorphic fabrics preserved in the gneissic amphibolite (Oma) and in the amphibole mylonite (Omm) are evidence of prograde, pre-Acadian, possibly Taconic metamorphism otherwise unknown in this part of Connecticut. The MLC is bound on the east by the Indian River Fault (IRF), which juxtaposes it against the Savin Schist (Osm & Oss). This fault and the rocks on either side are intruded by the Allingtown dike swarm (Sap). The timing of motion across the IRF is thus constrained as roughly Silurian by the high-grade fabrics in the gneissic amphibolite (Oma) and in the amphibole mylonite (Omm) are evidence of prograde, pre-Acadian, possibly Taconic metamorphism otherwise unknown in this part of Connecticut. The MLC is bound on the east by the Indian River Fault (IRF), which juxtaposes it against the Savin Schist (Osm & Oss). This fault and the rocks on either side are intruded by the Allingtown dike swarm (Sap). The timing of motion across the IRF is thus constrained as roughly Silurian by the high-grade fabrics in the MLC at 460 Ma (Armstrong et al., 1970) and the intrusion of the Allingtown dike swarm at ~418 Ma (Rankin et al., 2007). The MLC, Savin Schist, and Allingtown dike swarm were together thrust over the Wepawaug Schist along the SBF during Acadian and/or Alleghanian deformation. Thermo-chronologic investigation of the fabrics in the map area is needed to constrain the relative contributions of Devonian and Permian deformation. Complete exhumation of all units was achieved by the middle Triassic, when the basal conglomerate of the New Haven arkose was deposited (Hubert et al., 1992). Significant regional eastward tilting in excess of >35°, probably during the latter half of the Mesozoic (Roden-Tice & Wintsch, 2002), brought all units to their current orientations.

Software

Basemap data (topography, transportation, hydrography, and geographic names) were downloaded as .zip files from www.ct.gov/deep/gisdata and were processed using Esri ArcGIS 10.1. Field data were compiled using Microsoft Excel, and uploaded as .csv files to ArcGIS 10.1 for representation. Many representation layers were exported from ArcGIS as .ai files, and the final map was assembled in Adobe Illustrator 6.0. Stereonets were prepared with Allmendinger’s Stereonet for Windows (Allmendinger, 2004).

Data

Field data plotted on the map and in stereonets are provided in a supplementary table. Table 1.1 includes all field measurements, or attributes. Table 1.2 includes latitude and longitude coordinates for outcrop localities. Attributes may be related to localities by the ‘station’ field. Keys to columns and structure type listing are found in the metadata under “Comments.”

Geolocation information

Outcrops were located using a Samsung SCH-I400 cellular phone operating the GPS Essentials freeware application. Locations were recorded in geographical coordinates using the 1983 North American datum. Of several devices employed, including two dedicated Garmin units, the Samsung provided the most accurate and precise GPS coordinates (generally within 9 m), likely because the urban/suburban terrain and gentle topography allowed the Samsung device to use both satellite and Verizon Mobile networks in obtaining its triangulation. In rare circumstances when GPS was not available, location was obtained by pace-and-compass and notated on the fieldsheet.

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