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SHORT NOTES

Interaction between jointing and topography: a case study at Mt Ascutney, Vermont, U.S.A.

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Abstract—Jointing relationships indicate that the Cretaceous Mt Ascutney Intrusive Complex, Vermont, contains both cooling and unloading joints with similar orientations. This orientation pattern appears to be the result of the interaction of a Cretaceous joint fabric with topography and very near-surface stresses. Existing joints provide directions of weakness which influence subsequent joint orientations. In addition, topography controls and is controlled by the joint fabric. This study suggests that in the Mt Ascutney Intrusive Complex, the formation of joints during uplift and unloading is highly dependent on previous episodes of joint development.

INTRODUCTION

PARALLELISM between tectonic joint strikes and topographic trends suggests that joints may provide directions of weakness which erosive agents use to carve topographic landforms (Carlson & Kirkby 1972, Engelder & Sbar 1977, Plumb *et al.* 1984a,b). Topography may in turn influence the directions of later joint development, and the preferential re-opening of tectonic joints (Chapman 1958, Chapman & Rioux 1958, Bjerrum & Jorstad 1968). These are steps in the evolution from a purely tectonic joint fabric to a fabric which is a mixture of both tectonic and neotectonic joints. The purpose of this paper is to discuss the evolution of the total joint fabric during uplift and unloading in an area where fractures are the sole pervasive structure, the Cretaceous Mt Ascutney Intrusive, Vermont, U.S.A. The underlying hypothesis is that pre-existing fractures and topography both play an integral and inseparable role in the development of joints during unloading.

In the deep granite quarries of New England, joint density decreases rapidly with depth. Open, vertical joints are present predominantly within 10–12 m of the surface, with a rapid decrease in joint intensity observed below this depth although joint orientations generally remain similar. Sheet joint spacing changes gradually, and generally increases exponentially with depth (Jahns 1951, Johnson 1970). Gilbert (1904) reasoned that because sheet joints are confined to within a few hundred meters of the surface, sheet joint orientations must be controlled by topography. Jahns (1951) noted that sheet joints in the New England granite quarries were independent of lithologic control, as they cross-cut both xenoliths and foliation. Jahns (1951) also noted that there appeared to be two sets of sheet joints; a younger set orientated sub-parallel to the topography, and an older set which bore no apparent relationship to the topography. Jahns (1951) concluded that the older set had developed sub-parallel to the pre-glacial topography, and used the spacing of these joints to infer the depth of glacial erosion in New England. Because sheet joints are relatively young structures, termination relationships between sheet joints and other joints can provide constraints on joint age; joints which terminate against the post-glacial sheet joints must be young structures.

Geology of Mt Ascutney Intrusive

The White Mountain Magma Series of New England is a group of Mesozoic plutonic and volcanic centers (Billings 1945). A total of 30 intrusive centers distributed along a NNW-trending axis are known. The Mt Ascutney Intrusive (Fig. 1) is a Cretaceous member of the White Mountain Magma Series (Foland *et al.* 1985). Three units are present, in order of emplacement: (1) gabbro–diorite; (2) syenite; and (3) granite (Chapman & Chapman 1940, Foland *et al.* 1985). Topographically, the Mt Ascutney Intrusive forms a prominent monadnock which stands approximately 800 m above the floor of the adjacent Connecticut Valley. High relief is due, in part, to glacial erosion of the Connecticut Valley.

DYKE, VEIN AND JOINT FABRIC

Three types of brittle structures are present in the Mt Ascutney Intrusive: dykes, veins and unmineralized joints. The dykes are predominantly aplitic, granitic and pegmatitic in composition and average 5 cm in width and several meters in horizontal extent. They have a strong pattern of preferred orientation with two dominant

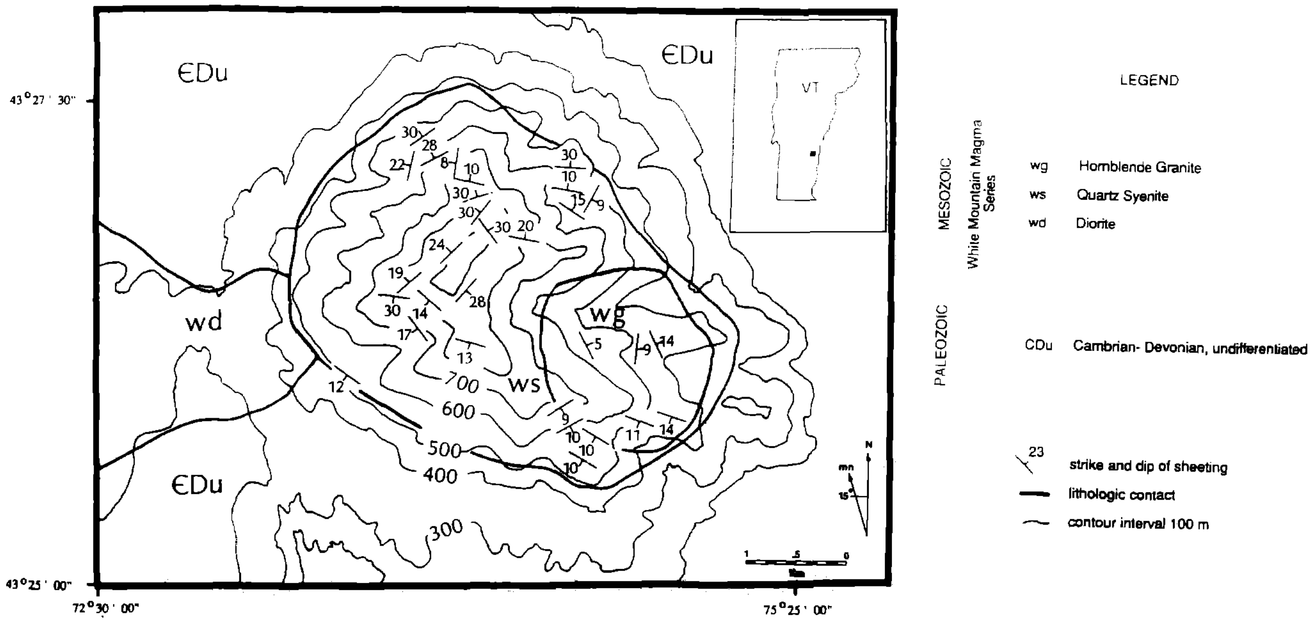

FIG. 1. Generalized bedrock geologic map of the Mt Ascutney Intrusive, Vermont, after Chapman & Chapman (1940) and Daly (1903).

orientation maxima centered at approximately N90°E and N360°E (Fig. 2a).

The veins (quartz + hematite) are planar, with a trace often in excess of 5 m. Spacing is variable, ranging from 1 to 10 m. The strikes are also concentrated into two maxima at N90°E and N360°E (Fig. 2b). Many veins are fractured down the center of the mineral filling, and have an unmineralized planar fracture surface extending past the vein tip. Dyke–host rock contacts are also fractured. In both cases the fracture traces average 5 m and are greater than the trace of the host vein or dyke. N90°E and N360°E orientation maxima result from the preferential orientation of the host structures (Fig. 2c).

Sheet joints are unmineralized, planar joints with dips of up to 30°. They cross-cut both dykes and veins and terminate against the open fractures in the veins (quartz + hematite). The orientations of these joints are broadly parallel to the domal topography of the Mt Ascutney

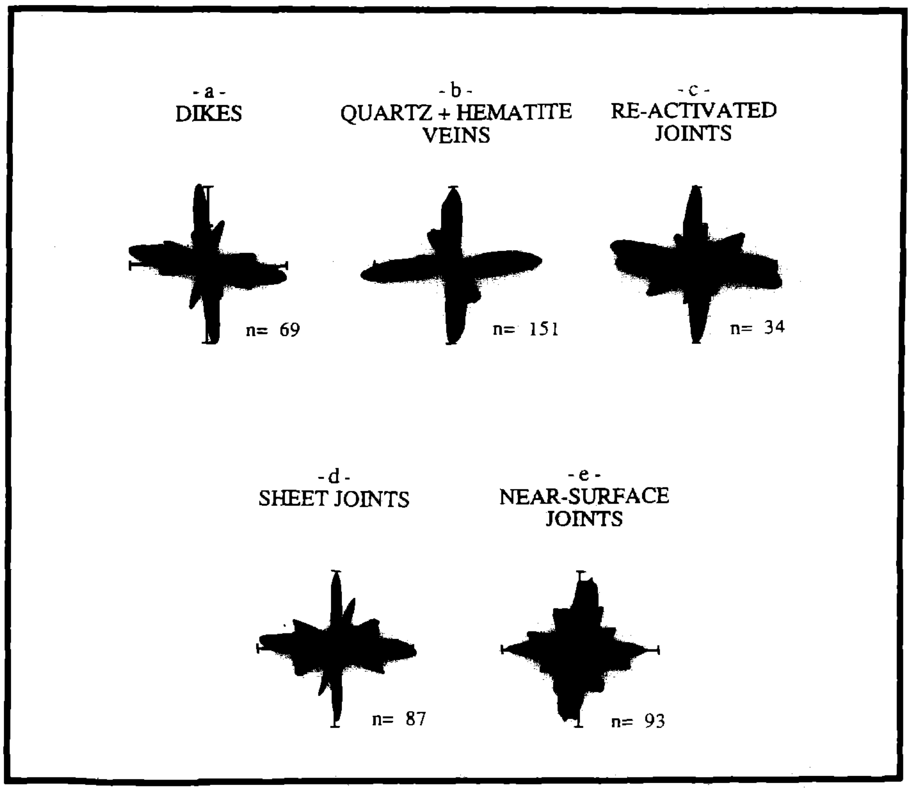

FIG. 2. Orientations of brittle structures in the Mt Ascutney Intrusive.

Monadnock (Fig. 1) but have a concentration of strikes similar to those of the dykes and veins, with maxima at N90°E and N360°E (Fig. 2d).

Open, steeply dipping to vertical, unmineralized, planar joints are the most common joints present in the Mt Ascutney Intrusive. Fracture trace lengths range from 0.1 to 5 m and have a strong pattern of preferred orientation, with maxima at N90°E and N360°E (Fig. 2e). They are distinct from the fractures in the veins (quartz + hematite) in that: (1) they do not re-fracture a vein; (2) they terminate against the sheet joints; and (3) their trace lengths are consistently shorter.

Joint formation

Aplite, pegmatite and granite dykes as well as the veins (quartz + hematite) must have formed during the intrusive and early cooling history of the Mt Ascutney Intrusive as suggested by two observations. First, no younger episodes of igneous activity are known in the Mt Ascutney area. Second, fluid inclusions in the quartz vein filling have high-temperature morphologies (Fleischmann in press). Because isotopic and fission track ages of members of the White Mountain Magma Series demonstrate that cooling was rapid, generally with 1 Ma of intrusion (Doherty & Lyons 1980, Foland *et al.* 1985), fluid inclusion formation must have occurred during the early cooling of the Mt Ascutney Intrusive. In addition, the vein (quartz + hematite) filling is found on the dyke–host rock contact, indicating that it is a later filling. On the basis of these observations, both dykes and veins are interpreted as Cretaceous structures.

Cross-cutting relationships show that all of the unmineralized joints developed after the formation of the quartz + hematite veins. Termination relationships among unmineralized joints show that the earliest to form were those which re-fractured the vein (quartz + hematite) filling. As this class of joints is older than the sheet joints, they must have developed at depths greater than that at which sheet joint formation was possible. It is impossible to further constrain the timing or depth of formation. Open joint termination relationships show that sheet joints were the next to develop. According to previous work (Gilbert 1904, Johnson 1970), these joints form when the least compressive stress is sub-vertical, and near the contemporary erosion surface. As commonly observed in other areas, sheet joint orientations are generally parallel to, and controlled by the local topography (Jahns 1951). The preferential orientation of sheeting seen at Mt Ascutney (Fig. 2) may indicate that preferential erosion along older, sub-vertical joints is in part responsible for the topographic slopes.

The final class of joints to form are those that terminate against the sheet joints. In New England granite quarries this class of unmineralized joints is confined to a zone between the present-day land surface and a depth of approximately 20 m. Unmineralized joints developed subsequent to post-intrusive cooling. Re-activation of veins and dykes could have occurred at any time following post-intrusive cooling. Because the bulk of the unmineralized joints are either sheet joints, or terminate against sheet joints, it is clear that the majority developed during uplift. It is also clear that joints formed during uplift have made use of the anisotropy created by older fractures, one example being the re-activation of veins as unmineralized fractures.

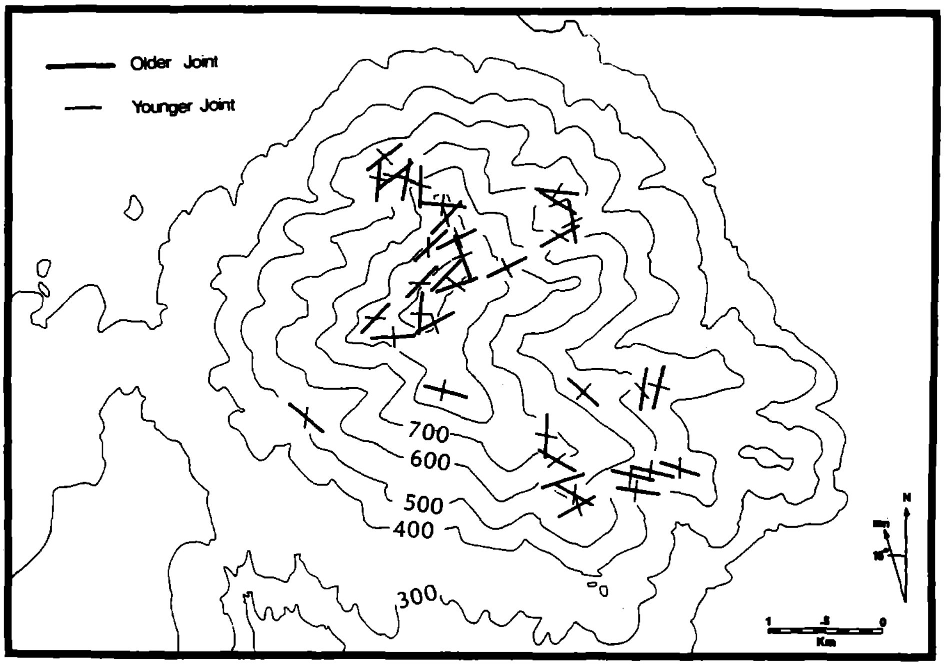

FIG. 3. Orientations of near-surface joint strikes in the Mt Ascutney Intrusive. Note the pattern of preferred orientation, with joints developed tangential and radial to the local slope conditions. Age relationships determined from joint-terminations generally indicate that joints striking parallel to the local slope are older than those striking perpendicular to the slope.

TOPOGRAPHIC EFFECTS ON JOINT FORMATION

Near-surface joint orientations and topography

Near-surface joints have a preferential orientation in the Mt Ascutney Intrusive (Fig. 2). These joints also have a preferential orientation with respect to the local topography. At each exposure two sets of near-surface joints are observed, with one set radial, and the second set tangential to the local topography (Fig. 3). This is best illustrated by re-plotting the data in a histogram, where joint orientations are plotted as the angle between joint strike and the strike of the local topography (Fig. 4). Because the bedrock slopes are exposed sheeting surfaces, sheeting strikes are used as the topographic slope orientation. The histogram shows that two orientations of near-surface joints are preferred; tangential orientations (where the angle between near-surface joint strike and sheeting strike = 0°) and radial orientations (where the angle between near-surface joint strike and sheeting strike = 90°).

In a study of joints at Mt Desert Island, Maine, Chapman (1958) observed that the final sets of joints to form had orientations which were radial and tangential to the topography. Chapman concluded that downslope creep, under the influence of gravity, was responsible for this pattern. The same explanation applies to the similar joint patterns observed at Mt Ascutney. The strong preferential orientation (Fig. 2) of near-surface joints indicates that near-surface joint formation occurs only where one element of the existing fracture fabric and the local topographic slope are approximately parallel, and joint re-activation is favored.

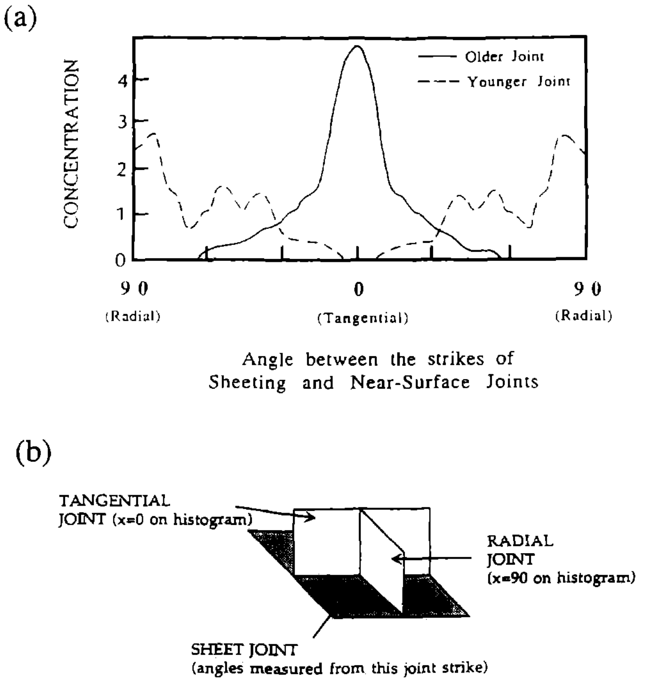

FIG. 4. Relationships between joint strike and topography. (a) In the histogram, joint strikes have been replotted in terms of their relationship to local slope conditions. Two curves are drawn, based on the relative age relationships between near-surface joints (b), one for older joints, and one for younger joints. The histogram shows that the pattern of orientations predominantly consists of radial and tangential joints. It also demonstrates that tangential joints (those which strike parallel to the local slope) are the older set.

Termination relationships and topography

Near-surface joint termination relationships, which traditionally define relative age relationships, are also topographically controlled. Near-surface joints are separated into two groups based on termination relationships, in Fig. 4; younger joints (joints which terminate against other joints) and older joints (joints which have other joints terminating against them). When the orientations of each group are plotted with respect to the local topography, it becomes clear that the 'older' joints are those generally tangential to topography, and the 'younger; joints are those generally radial to the topography (Fig. 4).

A termination of one near-surface joint against another indicates a relative age between the two fractures. Figures 3 and 4 show that the age relationship is in fact controlled by topography, with radial joints consistently younger than tangential joints. This relationship implies that tangential joint formation, where the joints are oriented perpendicular to the downslope-acting gravitational stresses, is favored over other orientations.

DISCUSSION

Hancock & Engelder (1989) suggest that shallow-formed joints generally have orientations which are controlled by the neotectonic stress field. Recent work has demonstrated that New England is under the influence of a principal horizontal compressive stress oriented approximately N60°E (Graham & Chiburis 1980, Pulli & Toksoz 1981, Yang & Aggarwal 1981, Moos *et al.* 1988, Plumb *et al.* 1988). If the near-surface joints were influenced by the contemporary tectonic stress field, they would show an orientation maxima at N60°E. Near-surface joints do not fit the pattern suggested by Hancock & Engelder (1989), indicating that, in the Mt Ascutney Intrusive, stress conditions during uplift have favored joint re-activation over new joint formation. However, this is an exception; neotectonic joints trending N60°E are generally common throughout New England (Hardcastle *et al.* 1989). The most likely explanation for this difference is the topographic relief: glacial erosion effectively isolated the Mt Ascutney intrusive from the neotectonic stress field by removing much of the surrounding country rock. Thus the joint development was influenced by pre-existing joints and gravitational, erosional and topographic forces, rather than neotectonic stresses.

CONCLUSIONS

I have attempted to show that in the Mt Ascutney Intrusive the orientation of joints formed during unloading is influenced by the orientation of the Cretaceous post-intrusive fracture fabric. In the Mt Ascutney Intrusive the veins, and to a lesser extent the dykes, act as zones of weakness. New joints form during unloading by exploiting the anisotropy. Downslope creep on sheet joints causes sub-vertical joint development, with joint orientations radial and tangential to the topography. Because sheet joints are preferentially oriented, this process produces a joint fabric with N90°E and N360°E orientation maxima, similar to the orientation of the Cretaceous vein and dyke fabric.

None of the joint maxima in the Mt Ascutney Intrusive result from the neotectonic N60°E horizontal maximum compressive stress. Neotectonic joints, following the definition of Hancock & Engelder (1989) are found only in the country rock. Thus, joint formation in the Mt Ascutney Intrusive results from a combination of the exploitation of the Cretaceous fabric and topographically controlled stress.

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