ANALYSIS OF DEFORMATION FEATURES AT THE POLLACK FARM SITE, DELAWARE[1]

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ABSTRACT

Several types of soft-sediment- and brittle-deformation features were observed in the Scotts Corners, Columbia, and Calvert formations at the Pollack Farm Site. Contorted and chaotic bedding, involutions, diapiric and wedge-cast structures, dissolution collapse features, and fractures, joints, and faults were observed in all units. Cold-climate freeze-thaw processes (congeliturbation) are the most likely causes of contorted and chaotic bedding and folding. The wedge-cast features have many similarities to frost-wedge casts. Some fractures, joints, and faults appear to have formed in an extensional stress field, possibly related to movement along the Smyrna fault zone, the border fault zone associated with an inferred buried Mesozoic rift basin. Other fractures and joints may have been caused by erosional unloading or weathering and mineralization processes.

INTRODUCTION

While the Pollack Farm Site was open for study between 1991 and 1993 we observed several types of soft-sediment- and brittle-deformation features in three formations exposed at the site, Scotts Corners, Columbia, and Calvert formations (Ramsey, 1998), and also at several places in the vicinity of the site after it was back-filled (Fig. 1). In this paper we describe and illustrate the features and interpret their origins.

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CONTORTED, CHAOTIC, AND FOLDED BEDDING

Contorted, chaotic, and folded bedding were observed within the Scotts Corners, Columbia, and Calvert formations (Fig. 1, sites a, b, and c; Figs. 2–5). The deformed unconsolidated sediments range in lithology from silty clay to sandy gravel and occur between 0 and 5–10 ft below land surface under east- and northeast-facing slopes. Fold amplitudes are as much as about 3 ft, and overturned folds with intrafold shear were observed. Orientations of axial planes of overturned folds indicate that horizontal movement was downslope toward the east. Many of the folds are detached at depth. The detachment surface occurs just above the Scotts Corners-Calvert contact at site a and in the upper mud unit of the Calvert at sites b and c. We have observed similar features at several other locations in Delaware.

The most severely deformed rocks were observed at site a within the Scotts Corners Formation (Figs. 2–4). They occur below a scarp-like topographic feature and are spatially associated with an undeformed Calvert-Scotts Corners contact and wedge-cast structures. At this location the Calvert beds are not folded. At sites b and c, it appears that the upper foot of a paleosol formed on the upper mud unit of the Calvert Formation was deformed into diapiric structures that intrude 0.5 to 1.5 ft into the overlying Columbia or Scotts Corners formations (Fig. 5). At site b the overlying Columbia is less than 5 ft thick. James E. Pizzuto (University of Delaware Department of Geology, unpub. rept., 1994) describes a similar feature developed beneath a closed depression at site c. The Scotts Corners here is less than 5 ft thick over the deformed beds of the Calvert.

[1] *In* Benson. R.N., ed., 1998, Geology and paleontology of the lower Miocene Pollack Farm Fossil Site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 47–53.

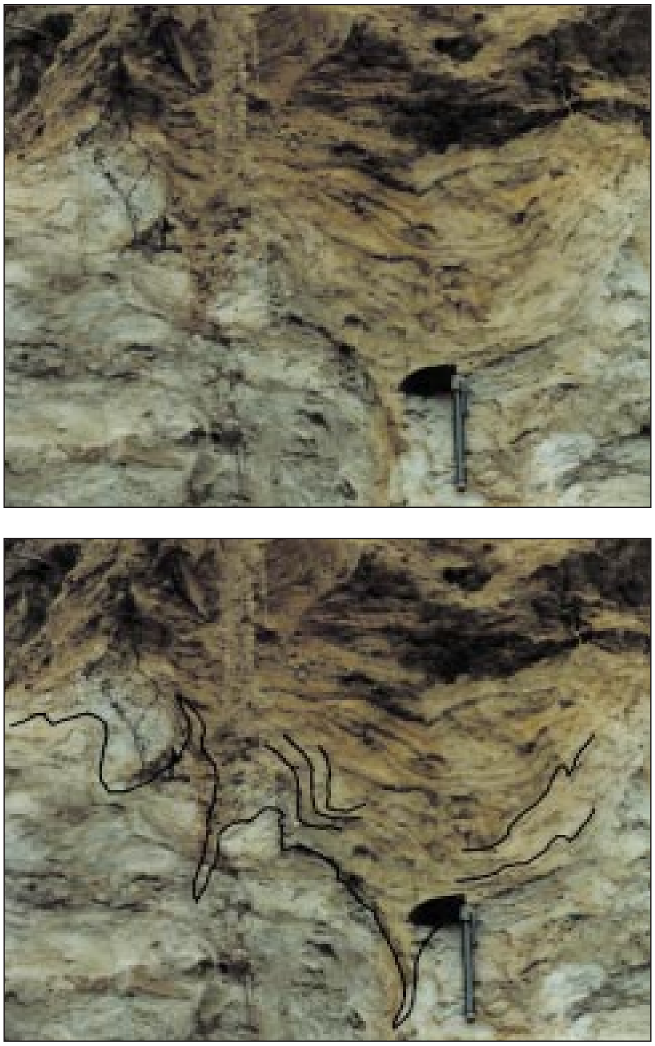

Figure 2. Photograph and interpreted line drawing of involute and contorted bedding in the Scotts Corners Formation at site a. Original land surface is located approximately 1.5 ft above the frame. Shovel handle is 1.5 ft long.

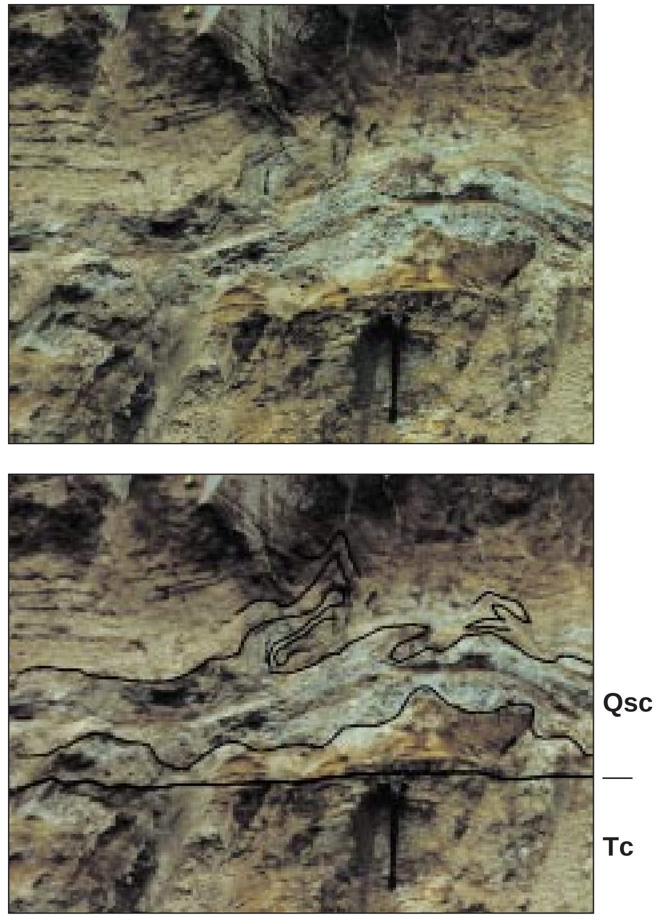

Figure 3. Photograph and interpreted line drawing of overturned and detached folds in the Scotts Corners Formation (Qsc) at site a. Original land surface is located approximately 1.5 ft above the frame. Tc–Calvert Formation.

WEDGE-CAST STRUCTURES

A few wedge-cast structures (Fig. 4) were observed at site a. They are near-vertical features that extend from near land surface down 6.5 ft into the underlying Scotts Corners. The casts were traced back into the face of the exposure at least 1 ft. The wedge casts are up to 1 ft wide at the top and taper downward. Some have a slightly sinuous profile, whereas others appear to be associated with involutions. Wedge-cast margins are commonly lined with vertically oriented granules and pebbles. Internal structure within a single cast ranges from structureless to faintly vertically laminated. The wedge casts appear to be filled with mixtures of the sandy materials overlying and surrounding the cast.

The amount of deformation associated with the wedge casts decreases with depth. The wedge casts completely disrupt bedding at their tops, with some surrounding beds rotated to near vertical near the cast margins. The rotation is predominately downward although some upwardly turned beds were observed. One cast is significantly deformed (Fig. 4). The top half of this cast appears to have been moved downslope farther than the bottom half.

No observations of the land surface were made prior to excavation, so it cannot be determined if the wedge-casts are connected or are part of a polygonal net. Aerial photographs (Fig. 1) show a variety of rounded surface textures on and around the site. These range from individual isolated features to net-like associations. The scale of the photography limits the resolution of individual features to larger than about 50 to 75 ft. From field observations many of the feature are small, seasonally wet, closed depressions. There are no circular or polygonal clast segregations associated with the depressions.

BRITTLE STRUCTURES

Three styles of brittle structures, fractures, joints, and faults (Figs. 6–9), are present in both the Columbia and Calvert formations. These structures were found in three orientations: horizontal, vertical, and conjugate sets about vertical sets. Fractures and joints exhibit no discernable offset. Fractures are differentiated from joints in that they are more irregular in form, less planar, and are not found in sets. Faults have measurable offsets of beds.

Orientation data from brittle features at the site are limited. In general, structures are upright and strike to the northeast. There is a second, minor set of fractures and joints that strikes to the northwest. Scant data indicate that there is another conjugate set striking west-northwest to east-southeast, less than 45° to the northwest-striking set.

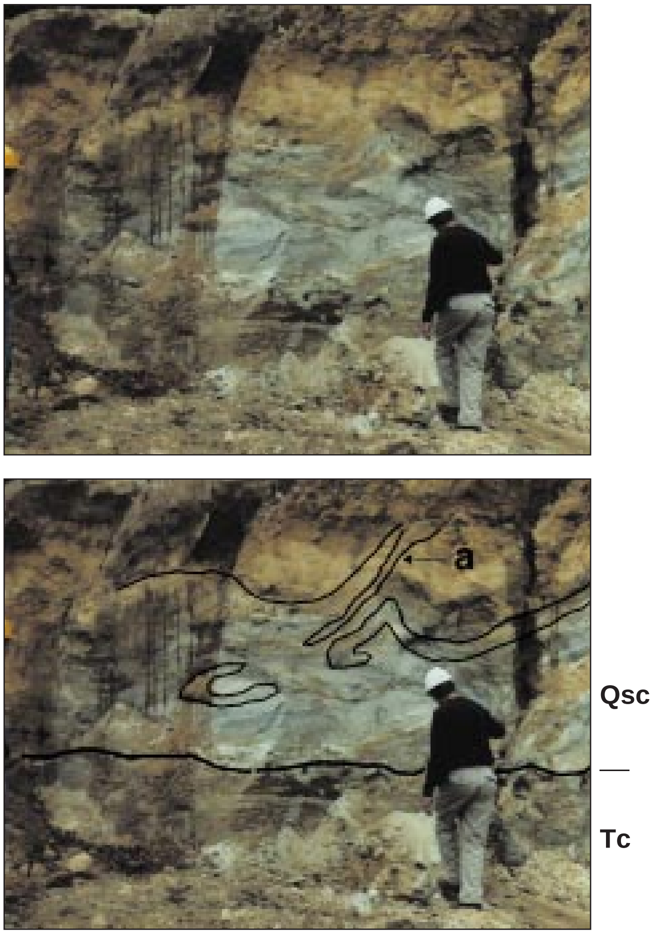

Figure 4. Photograph and interpreted line drawing of wedge-cast feature (**a**) and contorted bedding observed in the Scotts Corners Formation at site a. Original land surface appears close to top of frame on left side. Note that Calvert Formation (Tc) is not deformed.

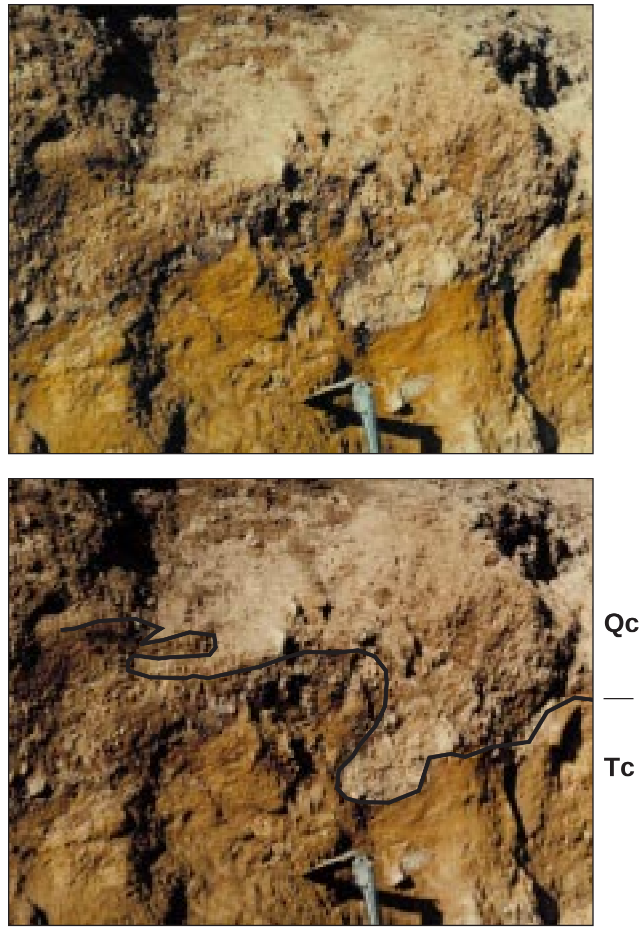

Figure 5. Photograph and interpreted line drawing of deformed Columbia-Calvert contact at site b. Diapir of weathered upper mud bed of the Calvert Formation has intruded approximately 1.5 ft into the Columbia Formation.

Figure 6. Photograph of scaly texture associated with intense fracturing and mineralization of the upper mud unit of the Calvert.

Joints and some fractures in the upper mud unit of the Calvert are typically closely spaced and regular in form. The structures commonly exceed the length of the outcrop, and terminations are rarely found. Conjugate patterns of joints and fractures are observable on a spacing scale larger than that of regular joints and are superimposed over the closer-spaced vertical joint sets. In some locations close to the contact with the Columbia Formation, the close spacing of the structures have a distinctive irregular form, giving the outcrop a scaly appearance (Fig. 6). This appearance has been accentuated by mineralization. In plan view, this intense fracturing forms polygons with spacings on the order of 1–2 in.

Where fractures and joints are present in the alternating sand and clay beds in the upper mud unit of the Calvert (Fig. 7), the structures are more clearly exposed in the clay beds than in sand beds. The structures appear to be continuous from clay bed to clay bed. Thin clay beds within a sand layer are commonly disrupted approximately in line with fractures in bounding clayey beds.

Near vertical joints, fractures, and faults were observed in the cross-bedded sand of the Calvert (Fig. 8). These features are present approximately 20 ft beneath original land surface. Joint or fracture spacing is on the order of 1–3 in. No measurements were made of fracture orientations, but it appears that they are similar to those observed in the overlying upper mud unit. Half-graben features with normal displacements on the order of 0.25–0.75 in were observed in sedimentary and biogenic structures. There are no good photographs of the offset features in the cross-bedded sand unit.

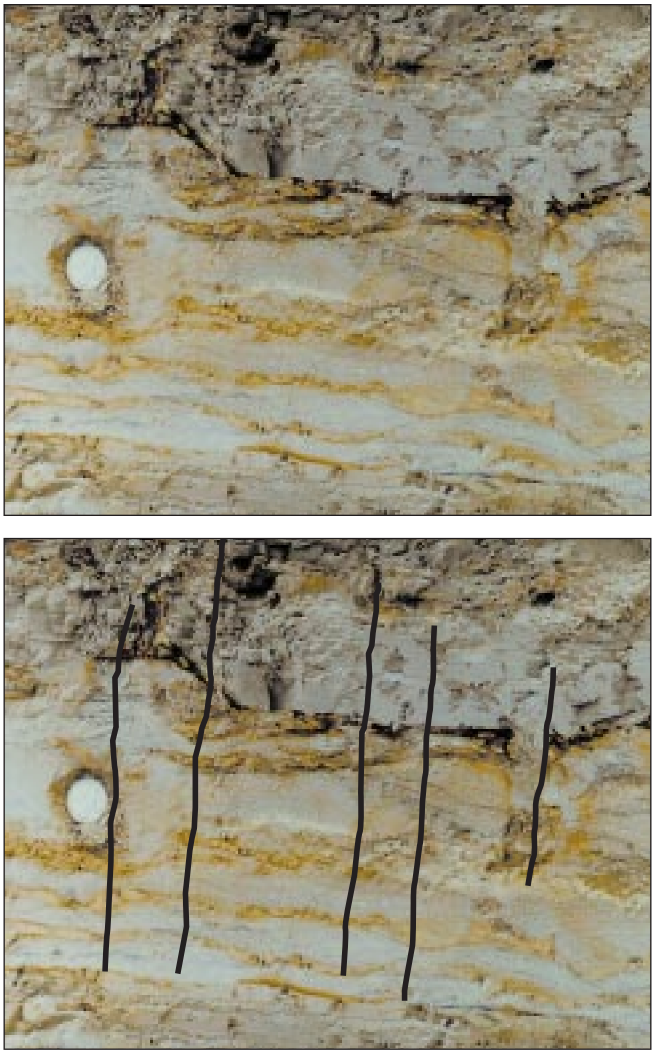

Figure 7. Photograph and interpreted line drawing of jointing and fracturing in alternating sand and mud beds within upper mud unit of the Calvert.

Faults with small offsets (<1 ft) are present within the Columbia near the contact with the Calvert at site b (Fig. 9). Half-graben features, commonly several in cascading succession, indicate normal displacements. Reverse displacements are less commonly present. Offsets appear to disrupt the upper mud unit of the Calvert.

DISSOLUTION-RELATED STRUCTURES

Structures are also associated with dissolution of the upper shell beds of the Calvert. Figure 10 (near site c) shows a sharp boundary between shelly beds and surrounding shell-free sand. The immediately adjacent sand has no visible sedimentary structures. The overlying beds a few feet away are gently warped down over the edge of the shell bed. Visible disruption of overlying bedding is restricted to within a few feet of the dissolved edge of the shell bed in overlying and horizontally adjacent materials. The dissolution features are not in close proximity to the undrained surface depressions found at the site.

DISCUSSION

Contorted, Chaotic, and Folded Bedding

These structures were observed in three different lithostratigraphic units of different ages at irregularly dis-

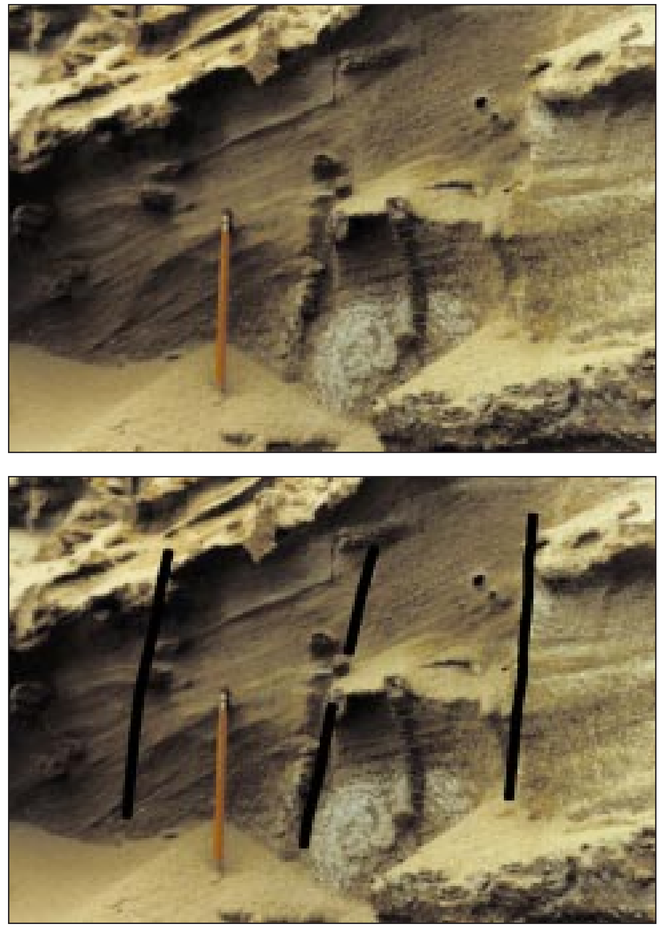

Figure 8. Photograph and interpreted line drawing of joints in cross-bedded sand unit of the Calvert. *Ophiomorpha nodosa* are cut by the joints.

tributed locations at the site, indicating that they were formed in response to highly localized conditions. Possible explanations for the structures follow.

Syndepositional Deformation of Water-Saturated Sediments

The features resemble flood-related syndepositional deformation structures in fluvial sediments as shown by Cant (1982, fig. 44) and Coleman and Prior (1982, fig. 5). Jordan (1964) and Spoljaric (1974) interpret the Columbia Formation as deposited in a fluvial environment that had fluctuating high and low energy components. Our interpretation of the chaotic sedimentary textures and structures observed at the site, however, is that they are not of syndepositional origin as they occur in three different lithostratigraphic units of different ages and depositional settings, and they cross contacts between the units.

Earthquake-Induced Liquefaction

The features do not fit the criteria identified by Obermeier et al. (1990) for earthquake liquefaction features reported in the Charleston, South Carolina, and New Madrid, Missouri, seismic zones. One of their key criteria for identifying earthquake liquefaction features is “evidence of an upward directed, strong hydraulic force that was suddenly applied and was of short duration” (Obermeier et al., 1990, p. 5). Features they cite as evidence of this criterion are vertically-oriented

Figure 9. Photograph and interpreted line drawing of small faults in the Columbia and Calvert formations at site b. Note that the features offset the contact between the Columbia and Calvert.

Figure 10. Photograph and interpreted line drawing of structures related to dissolution of upper shell beds. **a**–shell bed showing irregular top and bottom surfaces. **b**–the collapse zone where the overlying shell bed has been completely dissolved. **c**–the upper mud unit, which has not been significantly deformed over the collapse zone. The upper mud unit in this photograph also displays characteristic fracturing and weathering.

sand dikes, sand fissures, filled sand blows, and vented sand volcanoes. These features are not present at the Pollack Farm Site. Features at the site indicate both horizontally and vertically oriented forces that mixed sediment of different ages.

Cryoturbation or Mass Movement Related to Freeze and Thaw Cycles

There is a wide variety of evidence for cold climates existing in Delaware and the adjacent, then exposed, continental shelf during the Pleistocene. Ramsey (1993), Groot et al. (1995), Groot (1996), and J.J. Groot (written comm., 1991–1997) interpret that cold-climate conditions, as evidenced by boreal forest to taiga flora, existed throughout this region during one or more Quaternary glacial stages. Newby et al. (1994) report boreal forest and forested tundra-type pollen assemblages in sediment samples collected from beneath a pond located within 20 mi of the Pollack Farm Site (39°22'53" N, 75°40'33" W). On the bases of lithologic and textural criteria, Jordan (1964, p. 40) argued that the Columbia is derived from glacial outwash and was deposited during one or more glacial-interglacial cycles in the Pleistocene. In summary, although there is no clear evidence of continuous permafrost or of a climate that would create permafrost in Delaware, climatic conditions should have been sufficient to allow for a significant thickness of frozen ground to develop.

The folded, contorted, and chaotic bedding observed at the Pollack Farm Site is very similar to cryoturbation features shown in Hamelin and Cook (1967), Vandenberghe (1988), and Hamilton and Ashley (1993). Vandenberghe (1988) classifies these features as involutions, diapirs, and drops. The deformation features also are similar to those observed in the Coastal Plain of New Jersey that have been interpreted as forming in response to cold-climate processes (Newell et al., 1988).

Cryoturbation processes deform sediments through a variety of mechanisms, many of which are related to the buildup of excess water pressure in the subsurface from the freezing and thawing of interstitial water (Black, 1976; Vandenberghe, 1988; Hallet and Waddington, 1991). For example, excess hydrostatic pressure could have formed in a saturated zone between a downwardly freezing surface layer and the low permeability upper mud unit of the Calvert. The materials in the saturated zone will deform when the hydrostatic pressure exceeds the internal friction and/or cohesion of the materials. Excess hydrostatic pressure could also occur where buried lenses of ice form the lower low permeability boundary. Where excess hydrostatic pressure formed under a steeper topographic slope (e.g., site a) significant downslope mass movement occurred. In locations where the overlying Quaternary units are thin (<5 ft), the zone of excess pressure could have penetrated into beds of the older, more compact Calvert causing those beds to deform into upwardly moving diapirs. Cryoturbation features have also been attributed to forces caused by the volumetric expansion of water that occurs during freezing (Vandenberghe, 1988; French, 1988) and to thaw consolidation (Hallet and Waddington, 1991).

Wedge-Cast Structures

The wedge casts are very similar in size and morphology to ice and frost-wedge structures described and pictured in Hamelin and Cook (1967), Flint (1971), Black (1976), and Hamilton and Ashley (1993) . They are narrower and more sinuous than the wedge casts observed in southern New Jersey that Newell et al. (1988) described as frost wedges. Similar structures have been observed near Middletown, Delaware (Ramsey, 1994). The wedge-cast structures do not appear to be root burrows as there are no associated roots or organic matter. They are not likely to be desiccation cracks as they have formed in non-expandable material, in this case, sand (Black, 1976). Their three-dimensional forms demonstrate that they are not slump features formed at the edge of the excavation.

As discussed in the previous section, an assortment of data from Delaware and the adjacent continental shelf indicates that the local climate was sufficient to permit development of a significant thickness of frozen ground but perhaps not permafrost. A lack of permafrost conditions would mean that these features cannot be ice wedges (Walters, 1978; Black, 1976). The downward warping of the beds adjacent to the wedge casts also indicates that these are not ice-wedge casts. Hence, it is most likely that the wedge casts are fossil frost wedges that formed in seasonally frozen ground rather than ice wedges formed in permafrost (Walters, 1978; Black, 1976). The data are not sufficient to determine if the rounded closed depressions observed on aerial photographs are relict thermokarst features.

Brittle-Deformation Structures

Offsets on near-vertical faults in both the Columbia and Calvert formations indicate that they were formed in an extensional stress field. The orientations of major and conjugate joints also indicate their formation in an extensional stress field, where the axis of the principal minimum stress was oriented approximately horizontal with a northwest-southeast strike. These structures are similar to rock and photolineament features reported by others. Thompson (1980) found similar brittle structure orientations in Coastal Plain and Piedmont rocks adjacent to the Fall Line in nearby Pennsylvania, Maryland, and Delaware. Photolineament studies on LANDSAT imagery by Spoljaric (1979) show N-S, NE-SW, and NW-SE orientations, and a nearby possible fault.

The orientations and association of faults with vertical and conjugate joint and fracture sets indicate a tectonic origin possibly related to regional Cenozoic stress regimes. The faults and fracture and joint sets could be related to motion on deeper faults associated with the Smyrna fault zone (R.N. Benson, oral comm., 1990; Benson and Spoljaric, 1996, fig. 6) possibly associated with the border fault zone of an inferred buried Mesozoic rift basin (Queen Anne Basin), which, in turn, may be a reactivated Paleozoic thrust fault (Benson, 1992). Because the faults offset the Columbia-Calvert contact and there are no blocks of Calvert sediment in the Columbia, or other chaotic zone, it is highly unlikely that the faults were caused by syndepositional bank collapse or slope failure. The horizontal set of structures is probably related to erosional unloading.

One important factor in discussing the origin of fractures and joints is the coincidence of sulfate minerals alunite, jarosite, gypsum, and anhydrite (Nenad Spoljaric, written comm., 1992) within the highly fractured upper mud unit of the Calvert. The top surface of the upper mud unit is an unconformity, and the mineralization and fracturing are most intense close to this surface. As such, sulfate mineralization observed in the upper mud unit of the Calvert is likely to be a weathering phenomenon. Acid-sulfate soils commonly form on sulfide mineral-bearing deposits in oxidizing, wet and dry tropical, sub-tropical (Moormann, 1963), and temperate to cool-temperate climates (Postma, 1983). Pyrite is commonly observed in the lower half of the Calvert Formation (Spoljaric, 1988, 1996), the unit present at the Pollack Farm Site. The upper mud unit is interpreted to have been deposited in a tidal flat environment (Ramsey, 1998). The origin of some joints and fractures and the sulfate minerals in the upper mud of the Calvert could be related to cycles of wetting and drying typical of tidal flat deposits, or post-depositional weathering. It is possible that some of the intense fracturing could have been caused by desiccation during cold, dry periods; however, it is unlikely that these processes also caused the vertical fractures in the tidal-channel sands of the Calvert and fluvial sands of the Columbia and the horizontal fractures in the upper mud of the Calvert. Given the proximity of the mineralized fractures to land surface and the highly oxidized Calvert-Columbia or Calvert-Scotts Corners contacts it does not seem likely that the mineralized fractures were caused by hydrothermal processes, a possibility suggested by Spoljaric (1996).

Dissolution-Related Structures

The style of deformation, proximity to the shelly beds, and obvious dissolution front on the shelly beds documents that these features are collapse structures. The facts that the deformation associated with these features was restricted to within a few feet of the shelly beds and that the upper shell beds are not very thick (<3 ft) indicate that this process would not allow significant development of karst topography.

CONCLUSIONS

Several types of deformation features were observed in the Scotts Corners, Columbia, and Calvert formations at the Pollack Farm Site. Contorted, folded, and disrupted bedding; wedge-cast structures; and faults, fractures, and joints were observed. Several mechanisms are responsible for these features:

(1) It appears that cold-climate (near periglacial) processes had a strong effect on the near-surface sediments. Contorted, folded, and disrupted bedding was likely caused

by cryoturbation processes that occurred in seasonally frozen ground. The wedge-cast features have many similarities to fossil frost wedges that are interpreted to have formed in seasonally frozen ground. There is no clear evidence for the existence of permafrost.

(2) Some of the fractures and joints appear to have formed in an extensional stress field, possibly related to movement along the Smyrna fault zone, the border fault zone associated with an inferred buried Mesozoic rift basin.

(3) Some of the joints may have formed in response to erosional unloading forces or desiccation, weathering, and mineralization processes.

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