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by

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ICE-THRUST BEDROCK IN NORTHWEST CAVALIER COUNTY, NORTH DAKOTA[1]

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INTRODUCTION

During the summer of 1964, geologists of the North Dakota Geological Survey visited excavations under construction for Minuteman Missile installations in eastern North Dakota. An unusually well-exposed ice-thrust bedrock feature near Hannah in northwest Cavalier County was studied at one of these sites. This paper is a discussion of the geology at and near the site, and the stratigraphy, structural relationships, and possible methods of formation of the thrust feature. The particular missile site where the thrust was exposed will hereafter be referred to as the "Hannah Site."

GENERAL GEOLOGY IN THE IMMEDIATE AREA

Most of Cavalier County is underlain by the Cretaceous Pierre Shale which crops out in several places; some Niobrara Shale crops out along the Pembina Escarpment at the east edge of the county. Bedrock elevations are slightly higher east of the Hannah Site but west of there they drop markedly. The area around the Hannah Site is underlain by ground moraine till that averages between 10 and 30 feet thick. The till is slightly thinner east of the Hannah Site but it is much thicker a few miles to the west.

Observations of the cuts made for missile site installations revealed numerous exposures of two or more tills separated by out-

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wash, boulder pavements and buried soil profiles. The presence of paleosols on the lower tills at many of the missile sites indicates a period of time during which glacier ice was absent over the area. The lower tills were deposited during glaciations earlier than the one responsible for the deposition of the surface drift, but their ages are not yet known.

The lower tills are distinctly different from the upper tills at most of the missile sites studied. Generally, they are compact, hard, jointed and highly limonite-stained. The surface tills seldom have any of these characteristics. Where lower-type till occurs near the surface, the more typical surface drift is missing—either it was not deposited or it has been eroded away. The first of these possibilities is more likely because the area is only slightly eroded.

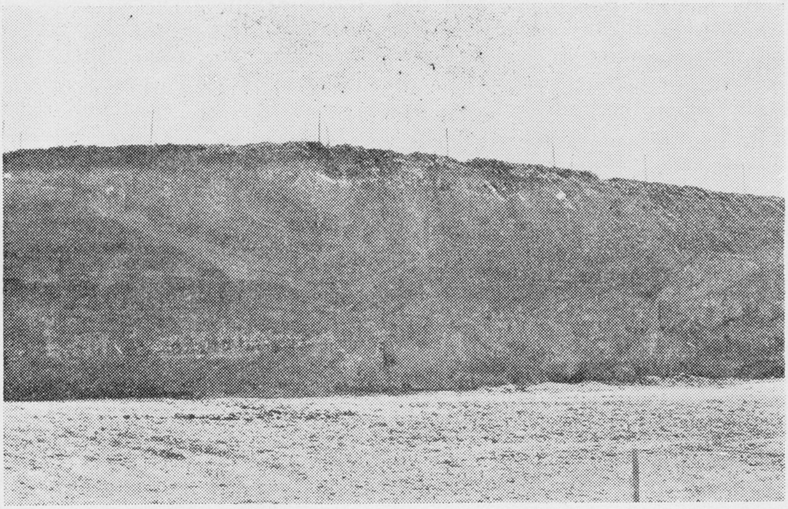
At the Hannah Site, two tills are separated by a block of overthrust shale. Both tills are very shaly clay loams with only a few granite and limestone pebbles. The lower till is much more dense, cohesive and uniform with a very few granitic and limestone pebbles; it is essentially ground-up shale. However, the presence of a few of these pebbles proves it is glacial drift and not bedrock.

DESCRIPTION OF THE HANNAH THRUST FEATURE

No topographic expression is associated with the subsurface ice-thrust feature at the Hannah Site. Ridges (washboard moraines) are abundant in nearby areas but because exposures are not present on them, it is impossible to verify whether they are the surface expression of similar ice-thrust features. Ice-thrust features described by Kupsch (1962) in an area of Saskatchewan to the northwest of Cavalier County have associated surface ridges.

Figure 1 illustrates the structural and stratigraphic relationships exposed by the excavation. The nearly vertical cut was about 30 feet deep. Beneath the topsoil and a 1- to 2-foot-thick surface till is a discontinuous pavement of igneous and metamorphic boulders and cobbles. Directly beneath the pavement, except at the westernmost end of the excavation, is shale that has been thrust over the lower till. At the westernmost end of the cut, the cobble pavement is directly underlain by the dense, sandy, shaly and pebbly till.

Three thrust-fault planes were exposed on the wall of the cut. The lowermost fault plane, A (Figure 1), is on the lower till surface. Its trace, which can be seen in only two dimensions, has an apparent dip of about 40° to the east. Highly contorted, ground-up, overturned and dragfolded shale lies on the till in many places. The thrust-plane trace is very sharp (Figure 2) as is the second fault plane, B (Figure 1), which is about six feet above the first. The shale above the fault trace is essentially undisturbed. Movement of the second thrust was along bedding planes. Because this fault trace was exposed on intersecting walls of the cut, it was possible to determine that the dip of the plane is 35° to the north and the strike



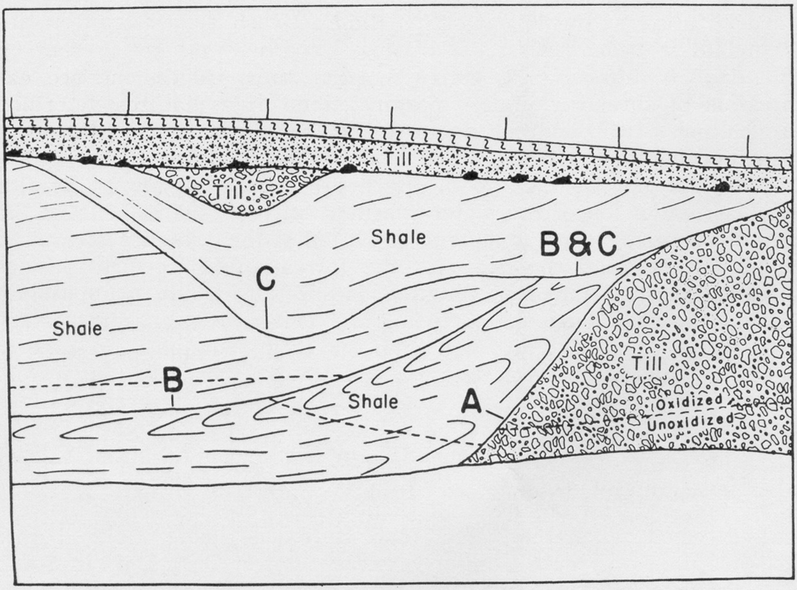


FIGURE 1—Photo of thrust with diagram showing the relationships. Thrust planes are lettered to correspond with the text. Excavation is about 30 feet high.

is 30° east of north, so movement must have been primarily from the northeast. The uppermost thrust plane, C (Figure 1), merges on the west with the thrust plane below it (B) and rises to about 25 feet above thrust plane B on the southeast. Generally, the shale on either side of the uppermost thrust plane has not been contorted. Movement along this thrust plane was probably mainly along bedding planes and from the north. The thrust plane dips northward at about 16°.

POSSIBLE METHODS OF FORMATION OF THE THRUST FEATURE

The thrust faults at the Hannah Site have spoon-shaped, concave-upward fault planes. According to Brinkmann (1953), different types of thrust structures can form depending on their position relative to the ice front. He says that near and ahead of the terminus, steeply dipping imbricate thrust blocks are pushed into shape and farther back behind the terminus, flat-lying folds result from frictional drag of the ice on the surface of the ground. The lowest thrust, A, is the most steeply dipping and the uppermost one dips the least. Perhaps, as the ice approached the area, the steep thrust (A) was pushed into shape and as the ice moved over, the less steeply-dipping thrusts (B and C) formed. The changes in direction of the thrusting may have resulted from changes in the ice flow direction as it thickened and became less controlled by the underlying topography.

Kupsch (1962, p. 593) stated that ice-thrust ridges may form in an area of thrusting in the marginal zone of a glacier where the upper part of the bedrock down to the lower limit of permafrost is incorporated in the glacier. The effective base of the glacier therefore would not be the top of the bedrock but the lower limit of permafrost on top of the water-bearing, unfrozen shales beneath the ground ice. Kupsch maintained (p. 596) that the presence of ground ice is an essential condition for the formation of ice-thrust ridges because, in their unfrozen state, sands and silts would not maintain their bedding during the thrusting. I think this is an unnecessary restriction because unlithified and unfrozen sediments do deform while maintaining recognizable bedding. I have seen intricately deformed silts associated with recent landslides at several locations in the Montana Rocky Mountains. The fault traces at some of these slides were very sharp, the materials a few inches on either side of the traces essentially undisturbed even though thousands of tons of materials had slid on the fault planes. Most of these landslides resulted when water-lubricated (and unfrozen) materials slid into too-steep highway cuts. Similarly, excavations at Oahe Dam in South Dakota revealed numerous large-scale slump thrust faults with unmodified slices of Pierre Shale between individual fault planes. Individual faults were hundreds of feet long. These faults were caused by slumping of the bluff during river downcutting, certainly in an

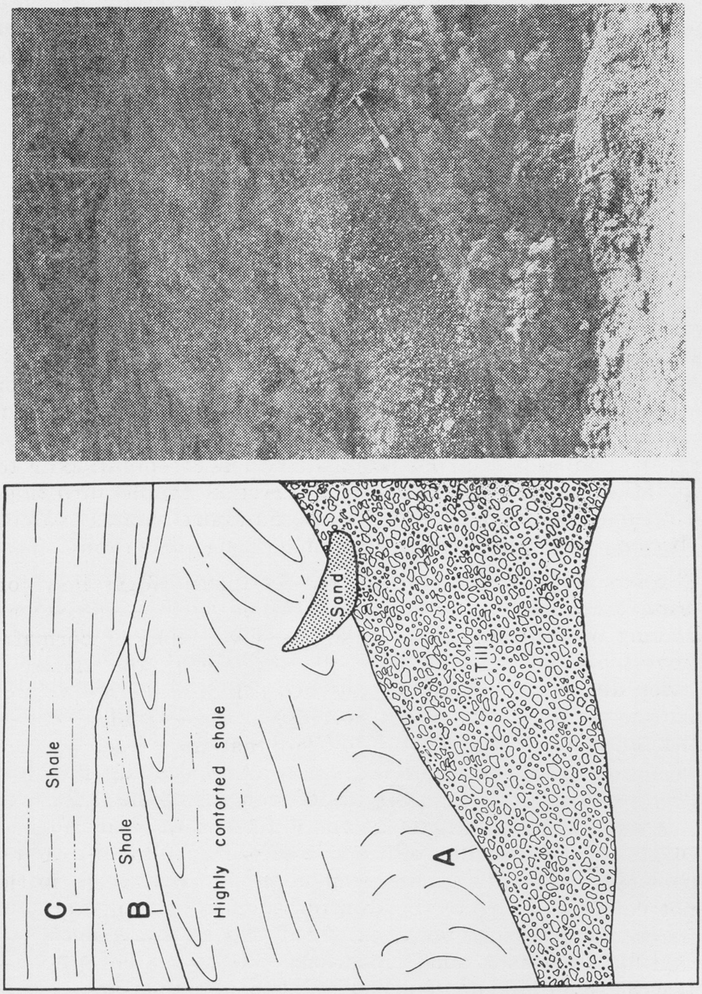


FIGURE 2—Close-up view of part of Figure 1 showing all three fault traces and the conditions of the materials above and below each trace. Shovel is about two feet long.

unfrozen condition. On the Missouri Coteau of central North Dakota I have seen similar slump faults and folds in collapse stagnation outwash. These, too, were probably unfrozen when they slumped into their present positions. During the present study, highly contorted sands and silts were observed in many exposures in eastern North Dakota. These contorted sediments have maintained their bedding planes in spite of the squeezing and thrusting they have undergone.

Engineering tests at the Hannah site show that the shales at the site have compressive strengths that vary from as little as 37 psi at 10 feet depth to as much as 378 psi at 80 feet depth. Therefore, taking the confining pressures at those depths into account, 37 to 378 pounds of stress per square inch are required to cause failure (crushing or shearing in any direction) of the shales. A glacier 650 feet thick exerts a static pressure of about 250 lbs/sq. in. (these figures are for clean ice; if the ice is debris-laden, the static pressures increase markedly). The ice was probably not this thick when it first advanced over the Hannah area but it must have been much thicker there when its margin was far to the south. The compressive strengths of the shale were undoubtedly exceeded by several times so it would not be at all surprising if all the shale had been completely crushed and all bedding had been obliterated. This did happen at many sites where as much as 100 feet of till composed almost entirely of crushed shale lies on undisturbed bedrock.

The compressive strengths given above for the Pierre Shale at the Hannah Site are certainly much greater than the strength of the shale along bedding or jointing planes. They are probably sufficient to allow the shale to fault and contort without being crushed or otherwise altered provided that the static glacier pressure does not exceed them (the compressive strengths) greatly. Such conditions might be obtained when ice first moved over the area.

Because the strengths of the shale along bedding and jointing planes are so much less than the static strengths of the shale, freezing is not a necessary condition to account for the undisturbed bedding above fault plane B and on either side of the uppermost thrust plane (C). However, where the main component of force exerted by the ice did not coincide with any bedding or jointing plane, the compressive strengths probably were exceeded and crushing such as that between fault planes A and B resulted.

Osmotic equilibrium may have played an important role in reducing the frictional resistance to sliding. As pointed out by Hubbert and Rubey (1959), anomalously high pore-water pressures may facilitate overthrust faulting. The high pore-water pressures spoken of by Hubbert and Rubey are caused in part by the considerable thicknesses of overlying rocks, a condition not met in the near-surface thrusting with which we are concerned. However, Hanshaw and Zen (1965) theorize that anomalously high pore-water pressures can result from osmotic processes. The Pierre Shale, because it has layers of bentonitic clay that could act as semi-permeable membranes to circulating ground water, might be particularly susceptible to high pore pressures at certain depths due to osmotic processes. The bentonitic clays in the shale are very continuous laterally and, if abundant fresh water was supplied by the nearby melting glacier ice, a relatively significant difference in the chemical potential of H_2O across the membrane might develop. The fresh water, supplied from above, would tend to migrate downward through the bentonite membranes toward high salt regions of relatively lower H_2O concentration. This would raise the H_2O concentration and pressure in those beds beneath the bentonite membrane causing the overlying beds to "float" on a layer of high-pressure water. If the dissolved components in a body of circulating ground water were filtered out by one or more beds rich in clay minerals such as bentonite, then under equilibrium conditions the pressure on the influx side might be anomalously high.

Because glaciers supply large amounts of fresh water, it seems likely that when they move over areas underlain by bentonitic shale such as the Pierre, that osmotic equilibrium might be a major factor in loosening material and forcing it upward ahead of and into the moving ice body. This should be especially true in areas such as North Dakota where the ground was probably not frozen to great depths during the glaciation. Such hydraulic raising of the bedrock may have played an important role in helping the glacier pick up its load of debris.

ACKNOWLEDGMENTS

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