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Gravitational Gliding in the Flagstaff Formation Near Soldier Summit, Utah

MOUNIR T. MOUSSA
Department of Geology
University of Puerto Rico, Mayagüez, Puerto Rico

ABSTRACT.—Twenty-seven secondary structural ridges superimposed on the southeastern flank of Clear Creek anticline between Soldier Summit and Colton, Utah, are here interpreted as caused by gravitational gliding of the uppermost limestone beds of the Flagstaff Formation. These gravity structures are parallel to the regional strike of the Flagstaff beds which form dip slopes along the southeastern flank of Clear Creek anticline. The gravity structures are classified into "wrinkle" folds, fractured "wrinkle" folds, and slip sheets. A "wrinkle" fold is a simple anticlinal fold, and a fractured "wrinkle" fold is a "wrinkle" fold in which the beds ruptured along the crest of the fold. A slip sheet is a gliding sheet of rocks which became detached from its original place on a dip slope and in which there is evidence for movement parallel to the plane of gliding.

The three types of gravity structures represent stages in the process of gravitational gliding which probably started during the latest cycle of erosion. When the erosional processes stripped a considerable part of the Colton Formation off the underlying Flagstaff, the limestone beds of the Flagstaff, unable to retain a simple form, started to glide under their own weight and a "wrinkle" fold was formed. As the tangential stresses due to the weight of the gliding mass continued to force the folded beds outward, the limbs of the "wrinkle" folds became steeper and the beds ruptured along the crest forming a fractured "wrinkle" fold. As the process of gliding continued, the upper limb of the fractured "wrinkle" fold broke off along the crest and overrode the lower limb as a slip sheet.

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INTRODUCTION

The regional structure underlying the Soldier Summit area, Utah, is a northeast-plunging anticline which has been named Clear Creek anticline (Walton, 1955, p. 404). The area west of White River between Soldier Summit and Colton, Utah, is part of the southeastern flank of the Clear Creek anticline (Text-fig. 1), and the relatively resistant limestones of the Flagstaff Formation (Late Paleocene-early Eocene) form dip slopes that average 9° E. This portion of the southeastern flank of Clear Creek anticline, between Soldier Summit and Colton, Utah, is superimposed by a number of strike ridges which are secondary structural features that are believed to have been caused by the slipping downward of the uppermost part of the Flagstaff Formation under the force of gravity.

The largest secondary structure on Aagard Ridge (Text-fig. 1) was the first to be discovered during a detailed geologic investigation in the Soldier Summit quadrangle, Utah. This structure is a secondary anticlinal fold in a relatively thin sheet of beds in the uppermost part of the Flagstaff Formation. Study of aerial photographs of the area revealed the ridge as a prominent feature though it might be overlooked in a ground survey. The ridge, however, does not stand high enough above the level of the surrounding slopes to produce any significant topographic expression on the quadrangle topographic map. The aerial photographs, moreover, disclosed the more important fact that there is a belt of such ridges which extends west of White River for almost eight miles south of Soldier Summit.

Terminology

The term gravitational gliding is used here as defined by de Sitter (1954, p. 322). De Sitter described gravitational gliding "as embracing all phenomena where gravity has been the cause of movement of relatively large and coherent superficial portions of the earth's crust. In this sense it does not include all such movements as landslides or slumping." De Sitter pointed out that gliding tectonics may range from a slab of sedimentary rock gliding down a surface and hardly undergoing any disturbance, to the gliding of a mass of highly incompetent strata.

Secondary structural features in which gravity undoubtedly played a prominent role have been called gravity-collapse structures (Harrison and Falcon, 1934, 1936). The term is used to describe strike and dome-like ridges which developed in Mesozoic and Cenozoic rocks in southwestern Iran where the strata were folded during post-Miocene orogenesis.

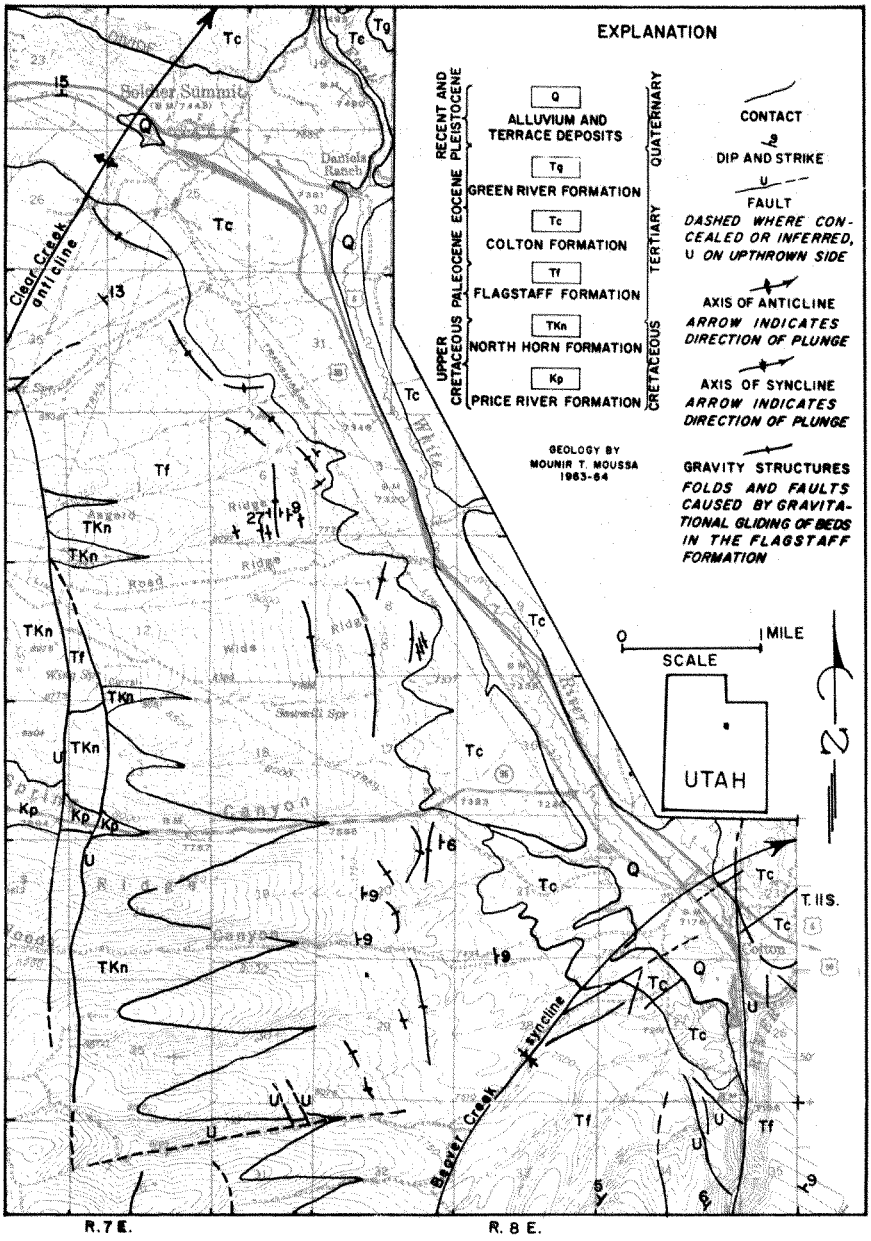
In the present work the secondary structures, where gravity has been the cause of movement, are simply referred to as gravity structures, and the term gravitation gliding is used for the process which produced them.

Geologic Setting

As indicated above, the structure underlying the Soldier Summit area is a northeast-plunging anticline called the Clear Creek anticline. The Clear Creek anticline is flanked on the southeast by a shallow northeast-plunging syncline called the Beaver Creek syncline (Walton, 1955, p. 405). (Text-fig. 1.) Three formations crop out west of White River between Soldier Summit and Colton; and from oldest to youngest these are the North Horn, the Flagstaff, and the Colton formations.

The North Horn Formation (Late Cretaceous-Early Paleocene) crops out in the headwaters of the canyons that cut transversely across the southeastern flank of Clear Creek anticline. The North Horn Formation is a variable assemblage of lithologic types which includes sandstone, siltstone, limestone conglomerate, limestone, and claystone in decreasing importance.

The Flagstaff Formation consists of limestone and interbedded siltstone and sandstone. Limestone of the Flagstaff is mostly gray and tan; however, it may be yellowish or brownish tan, dark gray, and rarely black. The limestone is mostly lithographic to sublithographic and rarely it is coarsely crystalline; it is mostly massive and locally it is thin bedded. Siltstone of the Flagstaff Formation is gray and rarely it is tan, brown, or reddish brown. The siltstone



TEXT-FIGURE 1.—Geologic map of the area west of White River between Soldier Summit and Colton, Utah, showing the southeastern flank of Clear Creek anticline and the superimposed secondary structures caused by the gravitational gliding in the Flagstaff Formation.

commonly has a considerable clay content and it is mostly calcareous. The siltstone beds are thin bedded. The sandstone is gray, and locally it has a greenish hue. The sandstone is fine grained and partly silty, and it is rarely medium to coarse grained. The sandstone is mostly of the quartzose type, and locally it has a high content of dark minerals which gives the sandstone a salt-and-pepper aspect. Cement of the sandstone is calcareous and probably slightly siliceous. The sandstone is mostly hard and resistant; it is commonly massive and locally it is thin bedded.

The Colton Formation (Early Eocene) in the area of this study consists of gray, salt-and-pepper sandstone, greenish-buff sandstone and siltstone that commonly weather golden brown, and claystone which ranges from deep red to variegated and gray. The Colton Formation is a valley-forming unit. The portion of the valley of the White River between Soldier Summit and Colton is a strike valley that follows the soft beds of the Colton Formation.

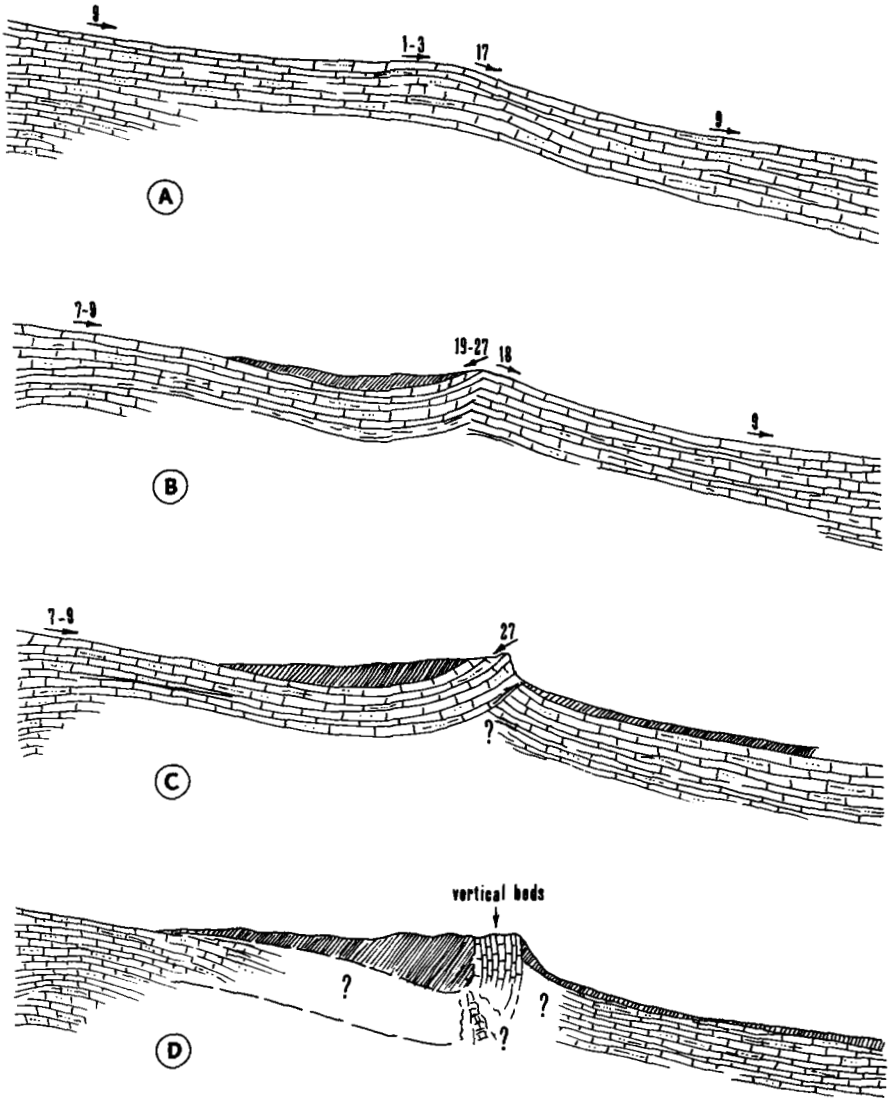
DESCRIPTION OF GRAVITY STRUCTURES

Gravitational gliding in the Soldier Summit area is exclusively restricted to rocks of the Flagstaff Formation. Only the uppermost part of the formation has been affected, but the exact thickness of this part is not known although it is certainly not more than a few tens of feet. Twenty-seven of these gravity structures were recognized in the Soldier Summit area. They are relatively small and the scale of the geologic map (Text-fig. 1) does not permit mapping their structural details. Only their trends are shown by plotting lines along the crest of the topographic ridges produced, and the crest of each is more or less coincident with the crest of the underlying secondary structure. Gravity structures range in length from a little more than 100 feet to about one mile. They occur either singly or in sets. They generally run more or less parallel to the regional strike of the Flagstaff Formation. The trend of the individual structures is either straight or slightly curved.

The gravity structures are either simple anticlinal or "wrinkle' 'folds, fractured "wrinkle" folds, or slip sheets. These three types represent three different structural relations which are here believed to represent a sequence, or stages, in the development of these gravity structures. Three structures, each an example of the three types of gravity structures, are described in the following paragraphs.

Wrinkle Fold.—The gravity structure in this case is merely a "wrinkle" or a simple anticlinal fold in the Flagstaff beds. An example of a "wrinkle" fold is the gravity structure on Road Ridge, Sec. 8, T. 11 S., R. 8 E. The structural relation in this example is shown in Text-figure 2*a*. On the downward side, at the base of the gravity structure, the beds have a normal dip of 9° E. Westward, the beds show a gradual increase in dip and attain a maximum value of 17° E. near the crest on the eastern limb of the structure. From the crest westward, the beds become almost flat attaining a dip of 1° to 3° E. There is no reversal of the direction of dip in this structure. Westward from the "wrinkle" fold the beds assume their normal regional dip.

Fractured "Wrinkle" Fold.—A fractured "wrinkle" fold is a "wrinkle" fold in which the beds ruptured along the crest of the fold, and consequently, the



TEXT-FIGURE 2.—Diagrammatic sketches of gravity structures. A. "Wrinkle" fold. B. Fractured "wrinkle" fold. C and D. Slip sheets which have undergone different amounts of deformation. Arrow and associated number indicate direction and amount of dip respectively. Hachures indicate colluvium.

beds on the upper (western) flank of the fold appear to truncate the beds on the lower (eastern) flank. An example of a fractured "wrinkle" fold is the gravity structure across the border line between Secs. 5 and 6, T. 11 S., R. 8 E. The structural relation in this example is illustrated in Text-figure 2*b*.

As in the case of a "wrinkle" fold the Flagstaff beds, downwards from the structure, have a dip of 9° E. The dip increases westward on the eastern flank of the structure and attains a maximum of 18° E. near the crest of the structure. At the crest the beds end abruptly against, and are truncated by, a sandstone bed which shows a range of dip between 19° and 27° W., in other words, in a direction opposite to that of the regional dip. West of the crest of the structure the area is covered by debris and no exposures are available for study. Farther west the Flagstaff beds assume their normal regional dip of 9° E. The structure underlying the covered area is most probably a shallow synclinal fold.

Slip Sheet.—A slip sheet is defined as a gliding sheet of rocks which has become detached from its original place on a dip slope and slipped down, remaining more or less intact (Harrison and Falcon, 1936, p. 92). Harrison and Falcon added that a drill would penetrate the beds twice. However, a slip sheet is herein considered to include any gliding sheet of rocks that has become detached from its original place on a dip slope and in which there has been evidence for movement parallel to the plane of sliding. An example of a slip sheet in the Soldier Summit area is illustrated by the lowermost gravity structure on Wide Ridge in W½, Sec. 8, T. 11 S., R. 8 E. The structural relation in this example is illustrated in Text-figure 2*c*. A slip sheet differs from a fractured "wrinkle" fold in that the upper limb of the structure broke off along the crest and overrode the lower limb. No exposures are available for study on the eastern flank of the gravity structure. However, the slope on the eastern flank becomes steeper westwards. The steepening of the slope seems to be a reflection of the expected increase in the amount of dip of the concealed strata. Along the crest, however, a set of beds dipping at 27° W. are excellently exposed. Westward from the crest the area is covered, and farther west the Flagstaff beds assume their normal regional dip of 9° E.

A more important feature, however, is displayed along the northern end of the structure; here, the strata along the crestal area have a vertical attitude. Exposures in the immediate vicinity both to the east and to the west are lacking; however, the attitude of the underlying beds is postulated from the behavior of the slope. The probable structural relations along the northern end of the structure are diagrammatically illustrated in Text-figure 2*d*.

Origin of Gravity Structures.—There seems to be no suggestion of a connection between the genesis of the gravity structures and that of the regional structure. Gravity rather than tectonic processes played the most important role in their development. Gravity structures originated primarily by the breaking off of the uppermost beds of the Flagstaff Formation and their moving downwards under the influence of gravity. The only relation, if there is any, between these gravity structures and the tectonic processes involved in the regional folding would be that the folding, if assumed to be of the flexure type, might have provided an easy plane for gliding. Billings (1954, p. 89, Fig. 77*a*) described flexure folding as being "analogous to the bending of a thick package of paper, and a very important factor is the sliding of beds past one another . . ." It is possible that one of the planes where the beds slid past one another during the folding of Clear Creek anticline acted as a gliding plane for the overlying sheet of rocks. It is likely that the gliding took place along

clayey beds. Whether ground water acted as lubricant or not during folding is hard to tell; however, it is not at all improbable.

The gravity structures are believed to be related chronologically to the latest cycle of erosion, and most probably they developed very late in the cycle. Their development seems to have followed the pattern illustrated in Text-figure 2. The first stage (Text-fig. 2*a*) is the formation of a simple anticlinal or "wrinkle" fold. The "wrinkle" fold on Road Ridge, described above, represents this stage. The formation of this "wrinkle" fold probably started during the latest cycle of erosion when the erosional processes stripped a considerable part of the Colton cover off the underlying limestone of the Flagstaff Formation. When the uncovered portion of the Flagstaff reached such a stage as to provide enough pressure under its own weight, it was not able to retain a simple form; the uppermost portion of the formation started to glide and wrinkle under the force of gravity. The "wrinkles" were formed by the plastic flow of the limestones at an elevation slightly higher than where the Flagstaff was still supported on the outside by the Colton beds.

In the next stage tangential stresses due to the weight of the gliding sheet continued to force the folded beds outward, and the limbs of the anticlinal fold became closer to each other. As the process continued, the downward limb of the fold was expected to bend over backwards to an overturned position. Field evidence, however, indicates that this did not take place anywhere in the area. The lower limb was pushed outwards only slightly as indicated by the mere steepening of beds. The downward limb probably was supported by the overlying Colton beds which provided enough force on the underlying Flagstaff limestone so as to oppose the pushing effect of the gliding mass. The upward limb, on the other hand, was relatively unsupported; the strength of the rocks and friction being the main forces acting against the force of gravity. This upward limb of the fold, therefore, became steeper; it turned, in most cases, through an angle of 36°, whereas the downward limb turned through an angle of 8°.

As the process of folding continued, the crest of the anticlinal fold became a line of weakness especially as it was subjected to continuous action of subaerial erosion. The upper limb of the structure broke off along the crest under the weight of the gliding mass and overrode the lower limb as a slip sheet (Text-figs. 2*b,c*). The fractured "wrinkle" fold described above and the slip sheet on Wide Range were produced in this manner.

The vertical attitude of some beds, as in the northern end of the slip sheet on Wide Ridge, represents a still later stage in the development of the gravity structures. The continuous pushing effect of the gliding mass on the lower end of the upward limb of the structure brought the beds of this limb to a vertical position, this latter limb being buttressed by the lower limb. This is illustrated in Text-figure 2*d*.

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