Geological Implications of Valley Rebound

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An air photo survey along some rivers in Central Alberta revealed the frequent occurrence of a raised valley rim in the ground surface adjacent to valleys where postglacial channels were incised through a region of low topographic relief. Subsequent more detailed studies lead to the conclusion that, in large part, these features are due to elastic rebound of the rock into which the valley has been eroded. Rebound of the valley floor occurs due to vertical stress relief and gives rise to a gentle anticlinal structure. This structure and the upwarping of the beds in the valley walls can be predicted by a mathematical model based on elastic behavior and incorporating modifications to deal with stratified rock masses.

Evidence of valley rebound was noted at the sites investigated and typical cases are presented. The amount of rebound varies with the modulus of elasticity of the rock and may be as much as 10% of the valley depth.

The upwarping of the beds will locally influence the dip of the beds. The rebound should be accompanied by interbed slip which would give rise to gouge zones. If these gouge zones occur near the base of the valley walls, they will have an important bearing on landslide activity. The raised valley rim has other geomorphological implications.

La photointerpretation a été utilisée pour l'analyse de quelques rivières, situées dans la partie centrale de l'Alberta. Cette étude a révélées que le soulèvement du rebord d'une vallée est de nature fréquente où des lits post-glaciaire furent incisés à travers une région de bas-relief topographique. Des études plus détaillées nous menèrent à la conclusion que ce phénomène est principalement dû au rebondissement élastique de la roche dans lequel la vallée fut érodée. Le rebondissement du fond d'une valée est causé par le relâchement des contraintes verticales et donne lieu a un léger anticlinal. Cette structure ainsi que la déformation des lits des versants de la vallée peuvent être prédites par un modèle de mathématique, basé sur la théorie d'élasticité et incluant les modifications nécessaires a répresenter la stratification des amas de roches.

Ce rebondissement a été mesuré sur quelques sites étudiés; des cas typiques sont aussi présentés. La grandeur du rebondissement est une fonction du module d'élasticité de la roche et peut aller jusqu'à 10% de la profondeur de la vallée.

Le gondolage des lits ne fait qu'influencer localement l'inclinaison de ceux-ci. Le rebondissement devrait être accompagné par un glissement des strates les unes par rapport aux autres, ce qui provoque la formation de minces zones argileuses entre celles-ci. Si ces zones se developpent près du pied du versant de la vallée, elles pourraient avoir une influence déterminante sur sa stabilité. De plus, le soulèvement du rebord de la vallée a d'autres implications géomorphologiques.

Introduction

The influence of geology on the design and construction of many civil engineering projects is well known. Transportation systems such as highways and pipelines are areas in which geologic input is important, and the close cooperation of the geologist and the engineer is of critical concern in earth dam projects. This paper discusses a phenomenon of interest to both the discipline of geology and of engineering.

A recent research project in the Department of Civil Engineering at the University of Alberta was concerned, in part, with the differential movements of footings placed in deep excavations and the rebound of the bottom of these excavations (DeJong 1971). The rebound of large man-made excavations in the Tertiary and Cretaceous rocks of the great plains of western Canada and north-central United States are well documented in engineering literature (see, for example, Smith and Redlinger 1953, Lane and Occhipinti 1963, Underwood *et al.* 1964, and Ringheim 1964). The immediate rebounds of the bottom of these excavations have been observed in the order of 1% of the excavation depth. They have presented engineering problems concerning the performance of the structures involved. The rebound of these excavation bottoms has continued, however, over significant periods of time. Fleming

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et al. (1970) show that the bottom of the Fort Peck Dam spillway in Montana (cut into the Bearpaw Formation) continues to rebound at the average rate of 0.04 ft (.01 m) per year and some 1 to 2 ft (.3 to .6 m) of rebound has occurred since October 1937 when readings began.

In a broad sense, river valleys can be considered as large scale excavations. The prime difference between natural valleys and artificial excavations is the time scale, thus the rebound of valley bottoms is greater than artificial excavations of equivalent depth. Associated with rebound of valley floors, is an upwarping of the beds in the valley wall. This upwarping, which increases as the valley is approached, is termed herein as "valley flexure". In regions of low topographic relief, a rise in the ground surface adjacent to the valley results from valley flexure and is termed a "raised valley rim". These features are considered to result from elastic rebound of the bedrock below the valley bottom due to the removal of the superincumbent overburden by valley excavation.

It is the purpose of this paper to present field evidence for valley rebound and to discuss briefly some geological implications of this phenomenon.

Geology and Physiography of the Study Area

The study area includes the southern parts of Alberta, Saskatchewan, and Manitoba, and eastern Montana and North and South Dakota (Fig. 1). This great plains area is of generally low surficial relief and is covered by a rather thin veneer of glacial deposits. The drainage system consists typically of deep, relatively narrow valleys, many of which are postglacial, excavated several hundred feet through the glacial deposits into the bedrock.

The near surface bedrock comprises a succession of marine and non-marine mudstones (clay shales), siltstones, and sandstones of Tertiary and Upper Cretaceous age. Minor amounts of bentonite and coal occur in the succession. The geology of this study area is discussed in detail by Williams and Burk (1964) and Taylor *et al.* (1964). The bedrock has been heavily overconsolidated by some 2000 ft (610 m) of sediments which were eroded during the Tertiary and by the continental ice sheets of the Pleistocene (Scott and Brooker 1968, Smith and Redlinger 1953).

Regional dips are commonly low, often in the order of tens of feet per mile, therefore, if continuous marker beds are present in a local region, stratigraphic interpretation is relatively easy. Normally, only beds of coal, bentonite, or limestone show sufficient continuity and uniformity in thickness to be used as marker beds. Bentonite beds have been traced over 20 mi (32 km) in the Upper Cretaceous Bearpaw Formation (Hake and Addison 1954) and were used as marker beds at Fort Randall Dam (Underwood 1964) and at Oahe Dam (Fleming *et al.* 1970).

The present drainage of the area was formed during the retreat phases of the continental glaciation some 12 000 to 25 000 years ago (Gravenor and Bayrock 1961, Scott and Brooker 1968, Fleming *et al.* 1970). Large volumes of meltwater rapidly eroded deep, steep-sided channels which were frequently ice-marginal or glacial lake spillways. Today, these valleys are typically 1 to 2 mi (1.6 to 3.2 km) wide, 200 to 400 ft (62 to 123 m) deep and have relatively steep valley walls except where landslide activity has flattened them.

A large number of sites for major earth-fill dams, as well as those locations where dams have been constructed, have been investigated within the study area over the last few decades. In addition to these, major bridges over some of the larger rivers have resulted in subsurface exploration programs. The stability of the local bedrock has been a controlling factor in the design of these structures and has resulted in intensive studies of the bedrock both from the point of view of its engineering properties as well as the major effects that minor geologic detail plays in the performance of the structure (Peterson 1954, 1958, Knight 1963, Ringheim 1964, Thomson 1970, Fleming *et al.* 1970). These investigational programs have produced geologic cross sections across a number of postglacial river valleys within the study area. Sites discussed in this article are shown in Fig. 1.

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FIG. 1. The study area.

hrough a region of very low topographic relief. This feature is considered to be due to elastic rebound of the rock comprising the valley wall and evidence to support this concept exists in the displacements predicted by the finite element method for an excavation made into an isotropic, homogeneous, elastic rock mass (Duncan and Goodman 1968). The displacements due to an excavation (or to valley formation) are illustrated in Fig. 2. Rebound of the bottom of the excavation occurs due to relief of vertical stress and an inward movement of the excavation walls occurs as a function of the lateral stress relief and the modulus of elasticity (E) of the bedrock. An upwarping of beds in the valley walls is predicted which results in a raised valley rim.

The mathematical model is based on elastic behavior and can be modified to deal with stratified rock masses. The rock properties, which can be varied for each layer, that are important in this model are the Modulus of Elasticity (E), Poisson's Ratio (ν), and the Coefficient of Earth Pressure at rest (K_0). E is

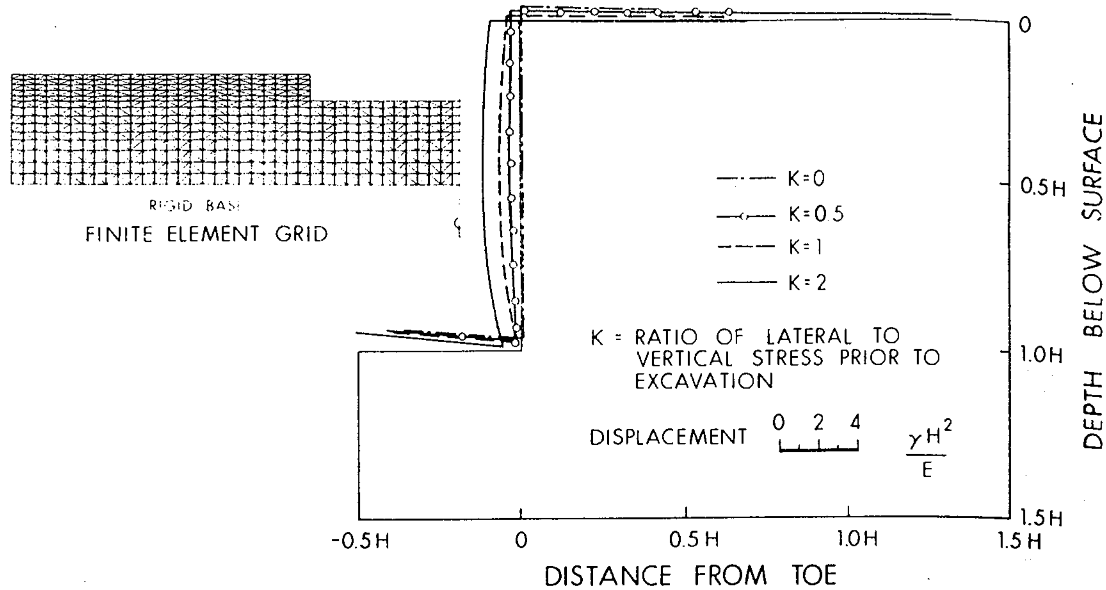


FIG. 2. Displacements adjacent to a vertical cut in a homogeneous, isotropic, elastic solid (after Duncan and Goodman 1968).

defined as the ratio of stress to strain at a given stress level, ν is defined as the absolute ratio of horizontal strain to vertical strain under the influence of a vertical stress and K_0 is defined as the ratio of the horizontal effective stress to the vertical effective stress. These parameters influence the amount of rebound but a detailed consideration of the mathematical treatment and the effects of parameter variation are considered to be outside the scope of this paper. The important feature is that the displacement patterns associated with valley rebound are predictable, at least in a qualitative sense.

It is important to note that the bedrock of the study area is characterized by low values of E. Moduli in the order of 10 000 to 20 000 p.s.i. (703 to 1406 kg/cm^2) are not uncommon in such formations as the Bearpaw and Pierre shales. Thus a change in stress, by either loading or unloading, will produce a relatively large strain.

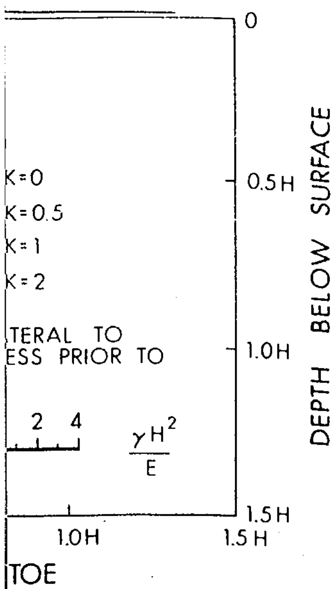
Examples of Valley Rebound

Government agencies and engineering firms engaged in dam and bridge investigation in the area were approached and a collection of valley cross sections was compiled. The resulting cross sections are primarily the result of continuous coring with double-tube core barrels such as the Pitcher Sampler (Morgenstern and Thomson 1971) or the Failing CB-19A core barrel (Hvorslev 1949). Core recovered is classified on the basis of visual inspection and routine engineering classification tests. Problems are often encountered with achieving core recovery in softer or fractured bedrock of the study area. An intensive, carefully conducted drilling program is required to produce a good picture of the stratigraphy along the center line of a damsite.

Distinct evidence of valley rebound was noted at every site in the study area where sufficient drilling had been done to detail the stratigraphy accurately and correlation of beds between test holes was possible. Selected examples are presented of cases where coring revealed a single anticlinal rise below the valley bottom and where an unwarping of the strata in the valley walls towards the valley edge occurred. Details of other sites are given by Matheson (1972). The anticlinal rise and the upwarping of the beds is often on a small scale compared to the size of the valley. Distortion of the vertical scale is used to bring out these features.

Hairy Hill Damsite

Hairy Hill Damsite (Fig. 1), located on the North Saskatchewan River some 80 mi (128 km) downstream of Edmonton, Alberta, was



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site (Fig. 1), located on the an River some 80 mi (128 of Edmonton, Alberta, was investigated by the Prairie Farm Rehabilitation Agency (P.F.R.A.). At the site, the valley is about 200 ft (60 m) deep and 1 mi (1.3 km) wide and is cut through bedrock of the Ribstone and Lea Park Formations (Upper Cretaceous). Thin coal strata and layers of very hard calcareous sandstone occur in both formations. Correlation of these marker beds show that some 6 ft (2 m) of rebound has occurred in the valley. The unwarping of these beds, which are normally flat lying, is indicated in Fig. 3.

The Ribstone Formation is composed mainly of uncemented to poorly cemented sandstone, the Lea Park Formation consists of gray marine shale with occasional thin carbonaceous sandstone or siltstone lenses or layers. The bedrock at the site is characterized by very low values of the Modulus of Elasticity (which, at one third to one half of the ultimate failure strength in the unconfined compression test, averaged 6300 p.s.i. for the Lea Park shale and 1100 p.s.i. (77.3 kg/cm^2) for the Ribstone sandstone) (P.F.R.A. 1970).

Ardley Damsite

The Ardley Damsite is located on the Red Deer River some 40 mi (64 km) downstream of the City of Red Deer in Central Alberta (Fig. 1). The site has been investigated by P.F.R.A. and by the Water Resources Division, Government of the Province of Alberta (Alberta Water Resources 1968).

The bedrock at the site is the Edmonton Formation of Upper Cretaceous age. The strata are nearly flat lying with a westerly dip of about 16 ft/mi (3 m/km). The original drilling encountered some poor recovery due to soft zones below the valley bottom and was supplemented by three large diameter test pits drilled along the valley floor (Brooker and Associates 1969). A study of the subsurface boring results along the center line (Fig. 4) indicate an anticlinal flexure below the valley bottom in the order of 12 ft (3.6 m). The section under the valley bottom is shown more clearly in Fig. 5 (Brooker and Associates 1969) when the results of the test pit exploration were added to the drilling results.

Unwarping of the 20 ft (6.1 m) thick coal seam in the valley walls is not evident from the test holes. The elevation of the coal outcrop revealed in a test excavation down the valley wall 600 ft (180 m) upstream of the proposed centerline, is about 12 ft (3.6 m) above the level suggested by the test hole data (Fig. 4).

Boundary Dam

Boundary Dam (Fig. 1) was constructed by P.F.R.A. on Long Creek near Estevan, Saskatchewan (P.F.R.A. 1956). Long Creek flows in a postglacial valley some 90 ft (28 m) deep and 1000 ft (300 m) wide cut through a thin veneer of glacial deposits and the bedrock of the Tertiary Ravenscrag Formation. The bedrock at the site consists of poorly lithified sandy to clayey shales, siltstones, sandstones, and several lignite beds which serve as marker beds.

The borehole logs (Fig. 6) indicate a rise in the lignite beds of about 10 ft (3 m) below the valley bottom. The upwarping of the beds on both sides of the valley is also evident although no surface expression of the flexure occurs at this site. Confirmation of the valley flexure is given in Fig. 7 which shows a distinct rise in the coal seams towards the valley wall. This photo, when compared to Fig. 6, illustrates some of the limitations in present core techniques in the soft bedrock of the study area.

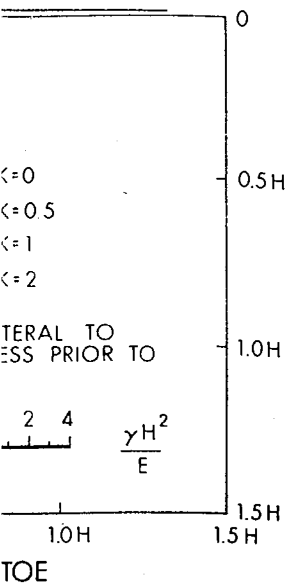
A similar valley anticline is documented in the drilling logs of an alternate damsite located several miles upstream of the dam (Matheson 1972).

James MacDonald Bridge, Edmonton

The James MacDonald bridge was constructed across the North Saskatchewan River in Edmonton, Alberta during 1970–71. The river lies in a postglacial valley some 200 ft (65 m) deep and 4000 ft (1200 m) wide at the site. In the valley bottom the river has carved a channel about 50 ft (16 m) deep and 600 ft (180 m) wide through the alluvial flood plain which mantles the valley floor.

The bedrock is the Edmonton Formation (Upper Cretaceous). The regional dip is low, 20 to 40 ft/mi (3.8 to 7.6 m/km) to the southwest (Carlson 1966). Geotechnical properties of the bedrock in the vicinity are discussed by Thomson (1970).

A center line profile across the valley is shown in Fig. 8. About 4 ft (1.2 m) of differential rebound across the channel can be observed by tracing coal and carbonaceous



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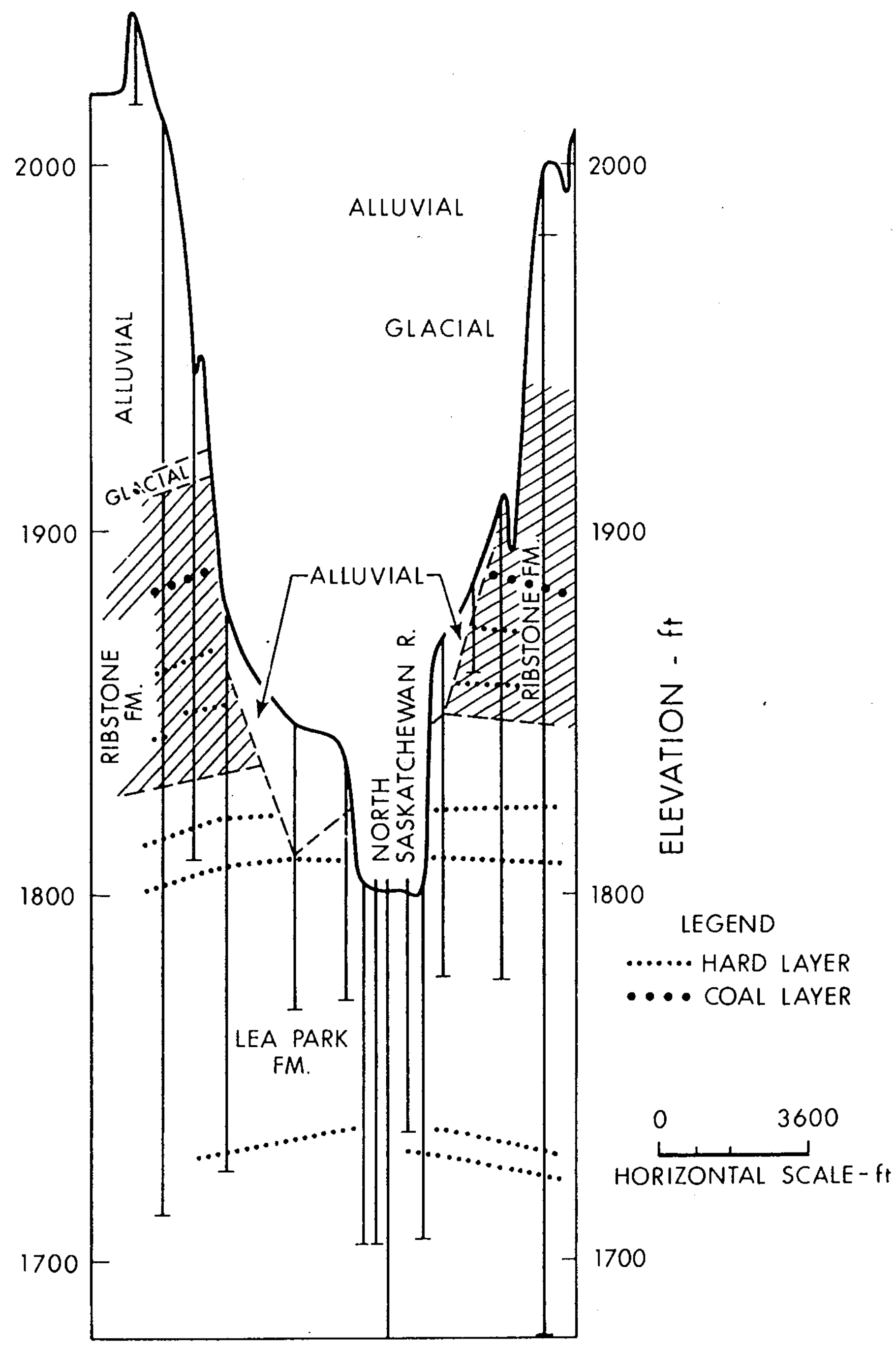

FIG. 3. Marker bed profiles at Hairy Hill Damsite (from P.F.R.A. plan 31059).

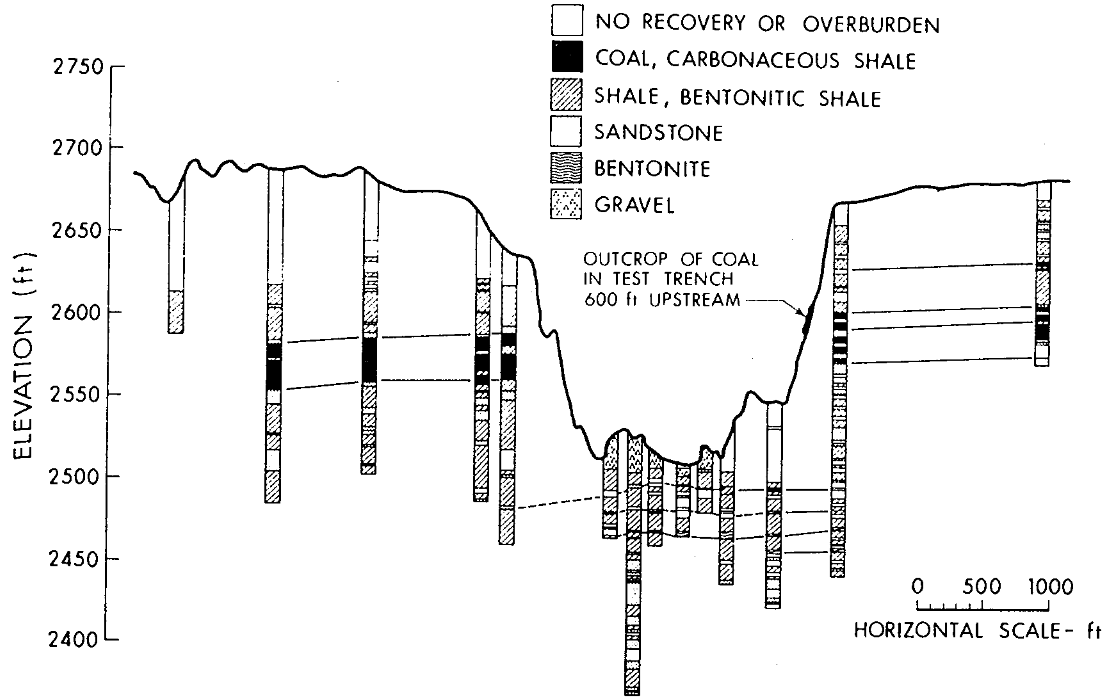

FIG. 4. Stratigraphy and test holes at Ardley Damsite (courtesy of Water Resources Division, Alberta Department of Agriculture). Note that: (1) Regional dip of the bedrock is 16 ft/mi (3.05 m/km) to the west and (2) Bedrock is Edmonton Formation (Upper Cretaceous).

shale beds and noting their upwarping under the river.

Garrison Dam

The valley of the Missouri River at Garrison Dam (Fig. 1) is some 2 mi (3 km) wide and 250 ft (80 m) deep. The center line geologic section for the dam shown in Fig. 9 (U.S. Corps of Engineers 1946) indicates considerable valley rebound. No single lignite bed can be traced across the valley due to the great depth of alluvium below the river but a rise of some 20 ft (6.1 m) in lignite beds can be observed in the valley walls as the river is approached. This is reflected on the ground surface at this site as will be discussed later.

The effect of the time factor is illustrated by Smith and Redlinger (1953) who compared the difference in elevation of lignite beds in the Fort Union Group (Tertiary) at the Garrison Damsite. One test hole was drilled on the top of the valley on the east abutment and another test hole in the flood plain near the east valley wall. These two holes were 659 ft (201 m) apart horizontally and their surface elevations differed by about 200 ft (61 m). The lignite beds below the flood plain were 4.6 to 7.4 ft (1.4 to 2.3 m) above the same beds below the valley wall. Observed rebound values for artificial excavations (Lane and Occhipinti 1963) were about one-half to one-quarter of the inferred natural rebound values. This difference is due to the long term continuing rebound during the many centuries since valley formation. Continuing rebound of the bottom of large scale excavations in the 120 ft (37 m) deep spillway cut at Garrison Dam have been documented by Fleming *et al.* (1970). The rate of rebound over the last two decades averages about 0.03 ft/yr (0.009 m) and is somewhat less than at Fort Peck.

Mechanism of Rebound

Figure 10 shows an idealized section illustrating the phenomena described in this article. The valley flexure and valley anticlines are apparently ubiquitous in the study area where the bedrock is characterized by a low modulus

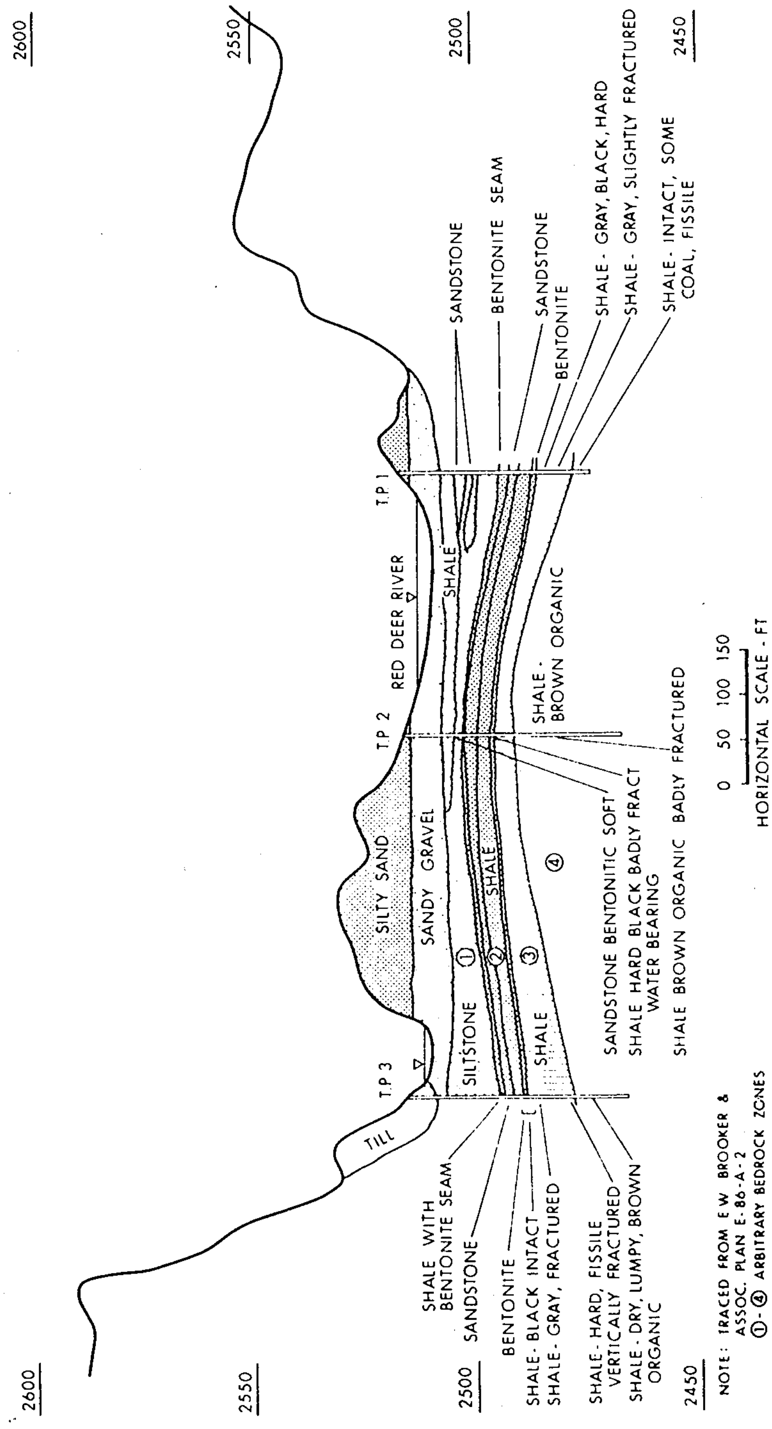

FIG. 5. Stratigraphy from large diameter test pits at Ardley Damsite.

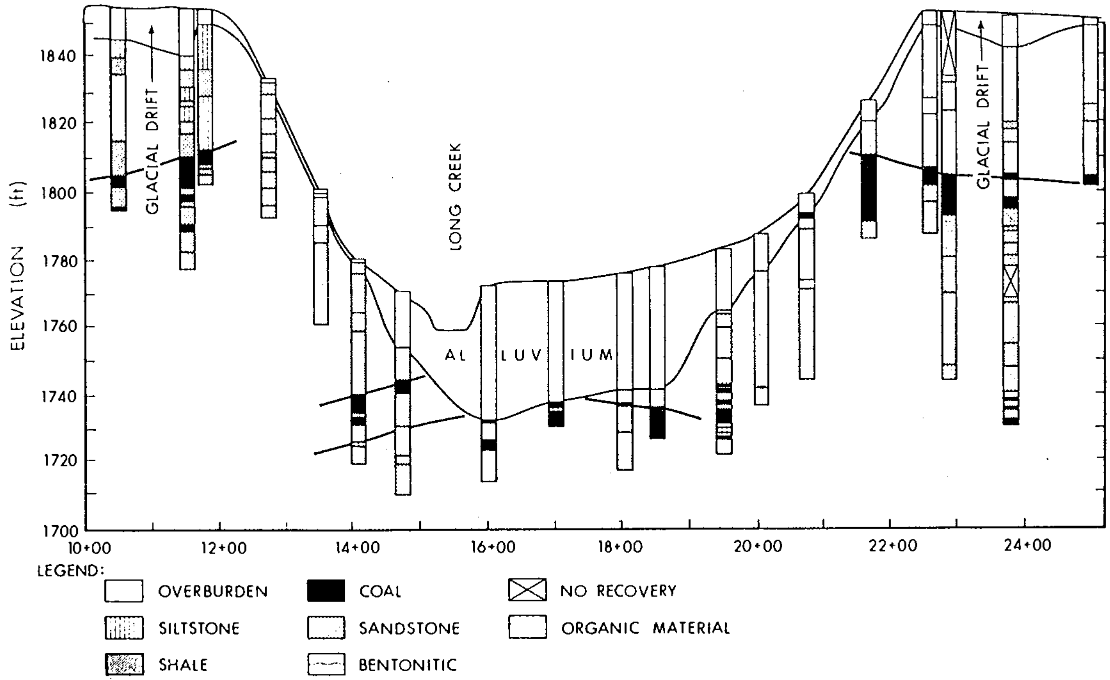

FIG. 6. Geologic profile at Boundary Dam Site 4 (courtesy of P.F.R.A.).

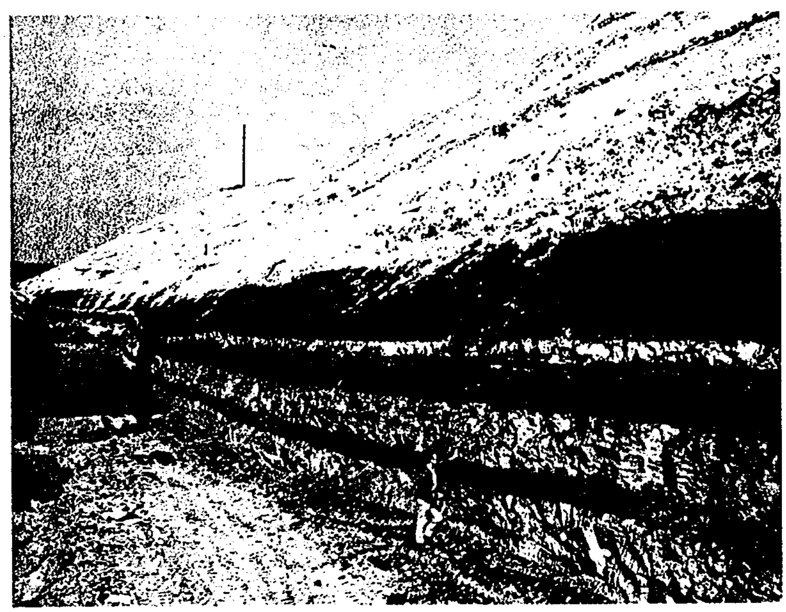

FIG. 7. View of east abutment core trench at Boundary Dam Saskatchewan. Note the three separate coal layers and the upwarping of the beds towards the valley (courtesy P.F.R.A.).

NOTE: TRACED FROM E.W. BROOKER & ASSOC. PLAN E-86-A-2
①-④ ARBITRARY BEDROCK ZONES

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HORIZONTAL SCALE - FT

FIG. 5. Stratigraphy from large diameter test pits at Ardley Damsite.

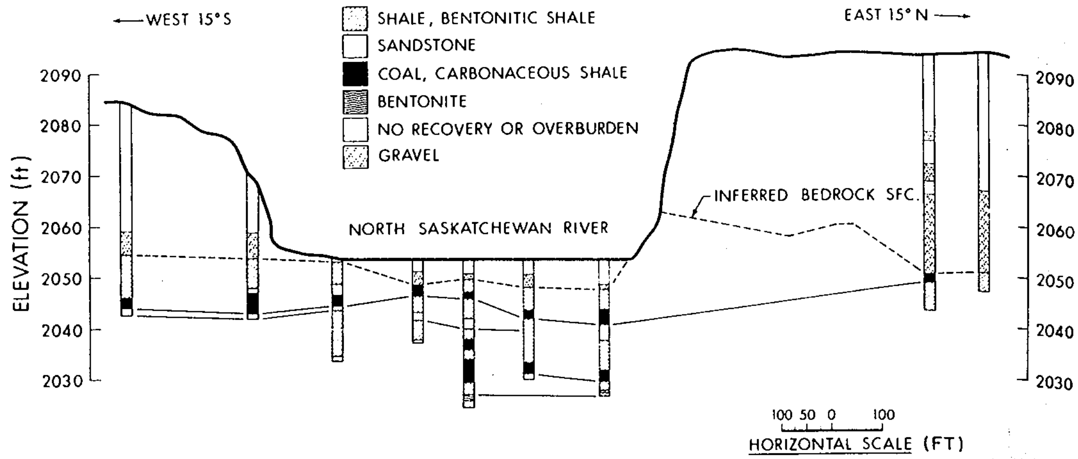

FIG. 8. Geologic profile at James MacDonald Bridge, Edmonton. Note that: (1) Bedrock is Edmonton Formation (Upper Cretaceous), (2) Elevations from city of Edmonton datum, (3) Regional dip of bedrock approximately 20 ft/mi (4 m/km) to the southwest. Courtesy of R. M. Hardy and Associates.

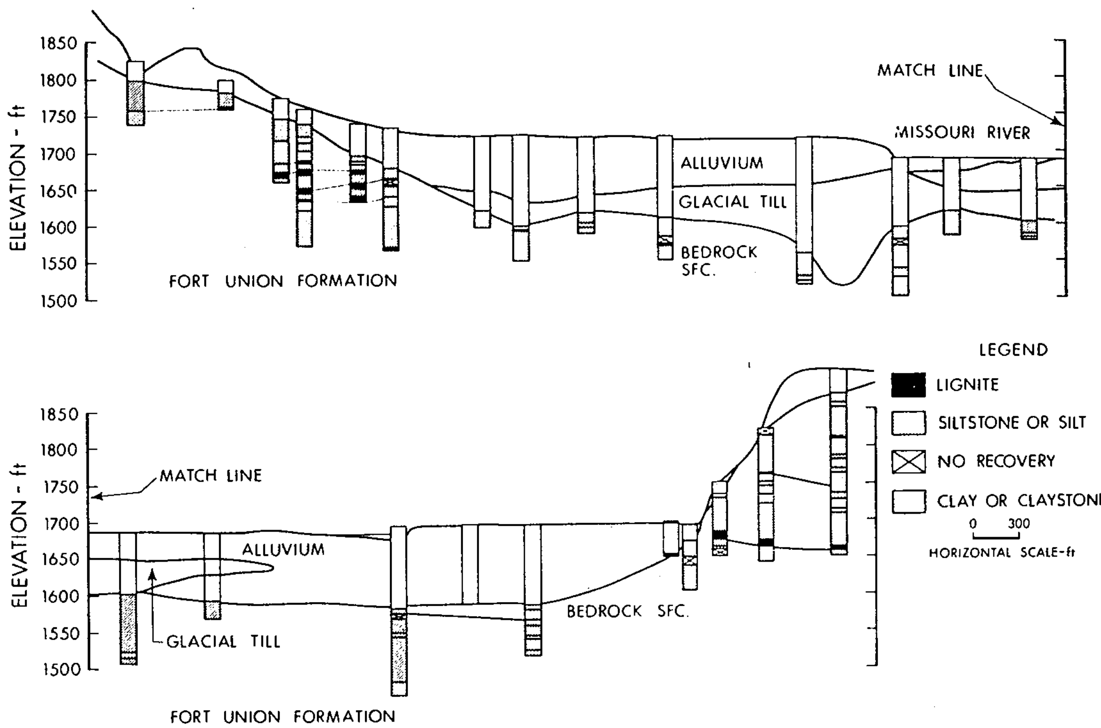

FIG. 9. Geologic section parallel to Garrison Dam axis. Note that only lignite seams thicker than 6 in. (15.2 cm) are shown. Courtesy of the U.S. Corps of Engineers.

of elasticity (E). Hence deformations due to stress relief are much larger than would occur adjacent to a valley cut through a stiff sedimentary, metamorphic, or igneous rock mass. The features observed in the field are qualitatively predicted by elastic theory as shown in Fig. 2—rebound of the valley bottom to form a 'valley anticline', upward flexure of the strata in the valley walls to form 'valley flexure', and a raise in the ground surface adjacent to the valley edge to form a 'raised valley rim'.

Similar anticlinal features have been docu-

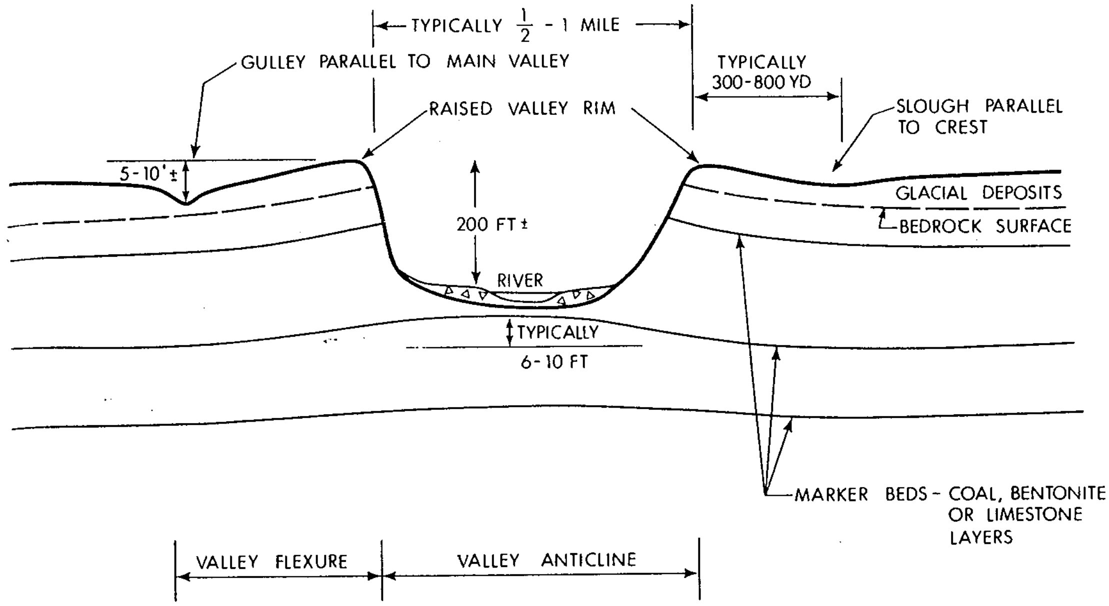

FIG. 10. Idealized section illustrating features resulting from valley rebound.

mented elsewhere. Ferguson (1967) documents gentle anticlinal rises below valley floors in the Allegheny Plateau in the U.S.A. Zaruba (1956) describes analogous phenomena in Rumania where Tertiary clayey sediments flooring river basins have been forced up into gentle anticlines arranged parallel to the direction of the river. These features were termed "valley anticlines". It should be noted that alternative mechanisms were proposed by Ferguson (1967) and Zaruba (1956) to explain their observations.

Table 1 summarizes the cases documented by Matheson (1972) and values of E for the bedrock. A marked trend occurs for larger amounts of rebound to occur below valleys cut into bedrock with a low modulus of elasticity. Rebound at the valley center ranges from 3 to 10% of the valley depth for sites where E is less than 50 000 p.s.i. (3515 km/cm^2) as is illustrated in Fig. 11. Artificial excavations in the bedrock of the area discussed previously have maximum rebounds of less than 1% of the excavation depth illustrating the importance of time-dependent rebound continuing over geologic periods of time.

The general trend of observed values of rebound agrees with the values of rebound predicted for the simple one-dimensional rebound mechanism illustrated in Fig. 11 and indicates that rebound due to stress release is the mechanism producing the features discussed in this article. It must be noted that the mechanisms used to delineate the process of rebound

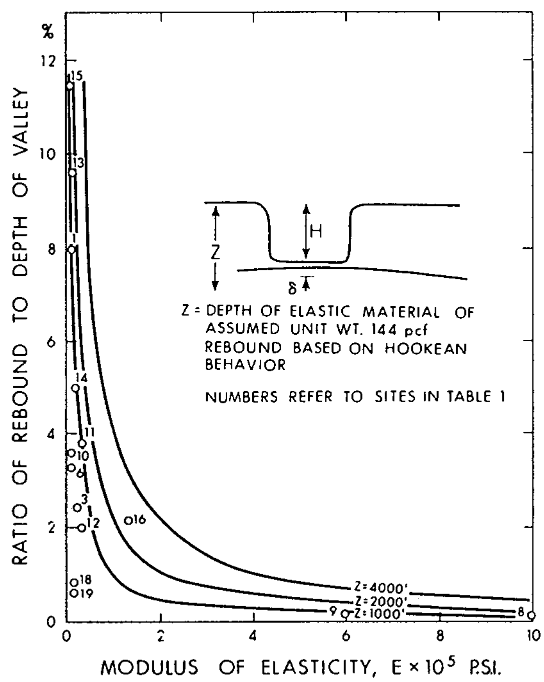

FIG. 11. Normalized maximum values of rebound versus modulus of elasticity.

TABLE 1. Compilation of maximum values of rebound and reported values of E

Site	Maximum rebound (ft)	δ/H	E (p.s.i.)
1. Ardley Damsite	12	.08	8400–12 000
2. Boundary Dam	6	.07	—
3. Carvel Damsite	5	.025	26 100 (shale) 53 000 (sandstone)
4. Hairy Hill Damsite	6	.033	6300 (Lea Park)
5. Ricky A Damsite	4	.036	—
6. Sounding Creek	5	.125	—
7. St. Mary Dam	1.5	.01	1×10^6
8. Three Rivers Damsite	0.5	.002	0.6×10^6
9. Tomahawk Damsite	7	.035	15 000 (sandstone)
10. Pembina 3A Damsite	5	.038	44 800–75 600
11. James MacDonald Bridge	4	.08	—
12. Garrison Dam	20	.09	14 000–40 000
13. Gavins Point	7	.05	20 000
14. Bowman-Haley	20	.12	1540
15. A.G.T. Excavation*	0.25	.007	6000–20 000
16. South Saskatchewan Dam*	—	.007	18 000

*Artificial excavation.

(simple elastic rebound) is an oversimplification of a rather complex problem, a more sophisticated method of analysis is given by Chang and Duncan (1970).

Features exhibiting an anticlinal structure have been created by ice thrust or ice push during the advance of the Wisconsinan glaciers (Kupsch 1962). These ice thrust ridges trend parallel to the advancing ice front. The anticlinal structures below the valley floors observed in this report do not bear any relationship to the direction of ice advance and, if one considers an ice tongue advancing up a valley, the anticlinal axes are perpendicular to the direction of advance. In addition, some of the valleys being considered are meltwater channels and erosion would likely have cut through ice thrust features. For these reasons, valley flexure is not considered to be due to ice thrusting.

Geological Implications

The occurrence of valley rebound provides an interesting and apparently widespread occurrence of a geologic structure that, in the broad field of geology, may be considered as a minor feature but which has major implications in many civil engineering projects.

The occurrence of valley rebound can be important in local stratigraphic interpretation immediately adjacent to major valleys incised into soft, horizontally bedded rock. It is to be noted that the bedrock of the study area is, for the most part, the poorly indurated rocks of the Upper Cretaceous and Tertiary ages. These rocks are characterized by low values of a modulus of elasticity as shown in Table 1. Beds below the valley floor form a gentle anticline and will be elevated above similar strata below the valley walls. The dip of beds that crop out in the valley walls will be an apparent dip and somewhat modified by valley flexure. The change in dip at most sites documented should be minor (in the order of 1 or 2°) although Underwood (1964) documents a downwarping of beds of up to 5° into the bluffs of the Missouri River at Fort Randall Dam (Upper Cretaceous Niobrara Formation).

The anticlinal structures in the valley bottom and the upwarping of the beds due to rebound in the valley walls should be accompanied by flexural slip between the originally flat lying beds. Changes in dip of up to several degrees appear to have occurred in the strata associated with valley rebound in the study area. The theoretical amount of flexural slip can be calculated (Norris 1967) and slip between beds in the order of several inches appears feasible. This slip, in turn, may give rise to 'gouge' or mylonite' zones which have been observed in the area.

The flexural or interbed slip can be simulated using the finite element program (Fig. 2)

FIG. 12. Gouge zo
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by introducing a thin laye
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wall. The differential m
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pressure also has a notab
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1.2 m) along bedding pla
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FIG. 12. Gouge zone in bridge pier excavation at James MacDonald Bridge, Edmonton, Alberta. (Note pocket knife for scale.)

by introducing a thin layer of low modulus of elasticity for example near the toe of the valley wall. The differential movement is strongly affected by the modulus of elasticity, the amount of slip increases as the modulus decreases. The value of the coefficient of earth pressure also has a notable effect, the amount of slip increases as the value of the coefficient increases. The mathematical model predicts, in a qualitative sense, the gouge zones.

The pier and abutment excavations for two bridges, constructed across the North Saskatchewan River in the city of Edmonton during 1969–1971, provided an opportunity to inspect the bedrock below the river bottom (Edmonton Formation of Upper Cretaceous age). The excavations were carried through a very thin alluvium and some 12 ft (3.6 m) into the bedrock. Thin, near horizontal, soft layers about 0.25 to 0.5 in. (0.6 to 1.3 cm) thick were observed in all the bridge pier excavations inspected. These layers, which were apparently composed of remolded material, occurred either at the contacts between strata of different lithology or at intervals of 2 to 4 ft (0.7 to 1.2 m) along bedding planes in beds of similar rock type. They were usually continuous and could be traced around the entire periphery of the pier excavations which were 20 by 40 ft (6.1 to 12.2 m). These layers exhibited pocket penetrometer strengths less than 0.5 tons (long)/ft^2 (.55 kg/cm^2). A pocket knife could be driven into the soft material under very slight pressure. Fig. 12 illustrates one of the layers in a bridge pier excavation in Edmonton.

Samples from the thin layers had essentially the same Atterberg limits and grain size distribution as the rock on either side of them. Hence it was concluded these features were not depositional in origin but were caused by shearing movements between beds. The movements are due to interbed slip resulting from rebound of the valley floor to form the valley anticlines documented in this article. They are considered to be a stress relief feature and may contribute to poor core recovery during drilling operations.

The presence of the thin soft layers below the valley bottom and, by inference, in the valley walls is considered to have important implications in landslide activity in the Upper Cretaceous bedrock of the study area. The soft layers, arising from interbed slip, would lower the shear strength along the near-horizontal bedding planes in the valley walls leading to a greater tendency for landslide activity.

The raised valley rim appeared to have geomorphological implications hence the cross sections available were augmented by field surveys. Simple ground surface profiles were obtained at locations where preliminary air photo study showed evidence of a raised valley rim. The profiles were surveyed at right angles to the valley wall using a 'Kern' precision engineering level and horizontal distances were paced. These surveys are considered to have an acceptable error for this project. The profiles extended far enough back from the valley edge to define the presence of a rim as well as the magnitude of the local relief in the area.

The sites at which surveys were conducted are shown on Fig. 13 as well as other sites at which there is evidence of valley rebound. The raised valley rim is a common, though not ubiquitous, feature. Along many of the valleys in the study area no trace of a rim appears to exist due to high local topographic relief, retrogressive landslides, or postglacial erosion. The

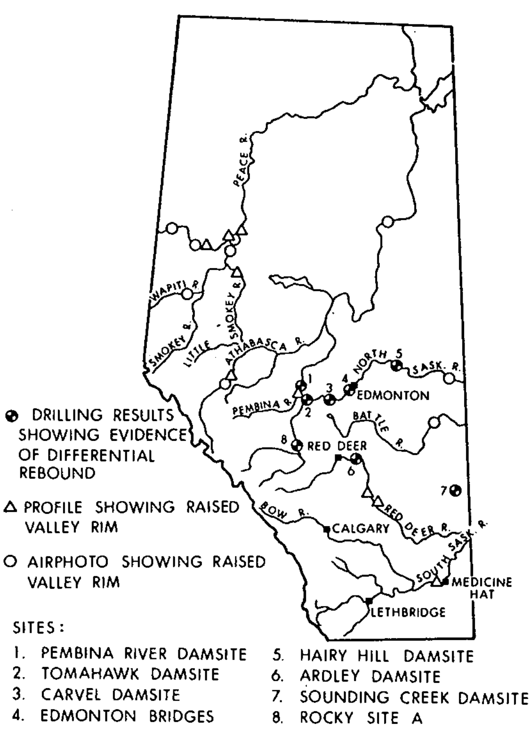

FIG. 13. Locations within the Province of Alberta showing evidence of valley flexure.

feature is best developed in areas of low topographic relief and thin overburden where the river valley is steep-walled and deep. Because it is a fairly common phenomenon and has geomorphological ramifications, three locations will be briefly discussed. Details of all the sites are given by Matheson (1972).

A typical profile across the South Saskatchewan River some 3 mi (4.8 km) upstream of Medicine Hat (Fig. 13) is given on Fig. 14. A rise of about 12 ft (4 m) in the ground surface starting some 1300 ft (400 m) back from the valley edge is clearly evident on both sides of the river. Three other profiles in the vicinity corroborated this observation. The river valley is postglacial, about 200 ft (61 m) deep and 5000 ft (1525 m) wide. Thirty feet (nine meters) of till overlies siltstones and mudstones of the Foremost and Oldman Formations of Upper Cretaceous Age.

Air photo studies of the Drumheller area, located northwest of Medicine Hat (Fig. 13) revealed well-developed raised valley rims. Figure 15 shows the location of surveys made along Michichi Creek about 2 mi (3 km) east of Drumheller. The valley immediately east of the plateau is some 400 ft (120 m) deep, the tributary valley to the west is about 200 ft (60 m) deep. A veneer of till 20 to 30 ft (6 to 9 m) thick overlies the Edmonton Formation. The profiles are shown on Fig. 16. The rise of 5 ft (1.6 m) occurs along the east side in a horizontal distance in the order of 25 ft (8 m) back from the valley edge. The rim effect on the west side appears less pronounced due to erosion. The feature is visible in the field as shown in Fig. 17.

The raised valley rim has been observed along the Missouri River. The project report for the Oahe Dam near Pierre, South Dakota (USCE 1948) described the ground surface as sloping landward from the valley wall thus leaving the rim edge as the highest portion on the left side of the river. In certain areas the rim effect is visible on both sides of the valley. Fig. 18 is a profile across the Missouri River 2 mi (3 km) downstream of Oahe Dam (Crandell 1958). The same phenomenon occurs elsewhere along the Missouri River as "at many places in the State, upland surfaces immediately adjacent to the trench slope away from the Missouri River" (Crandell 1958, p. 42). It

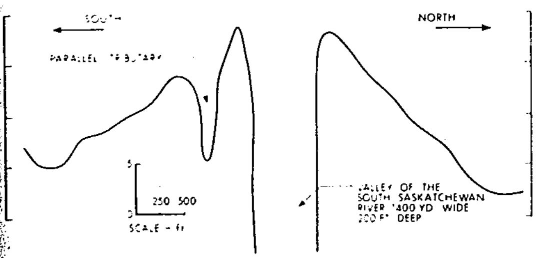

FIG. 14. Ground surface profiles on the South Saskatchewan River near Redcliff, Alberta.

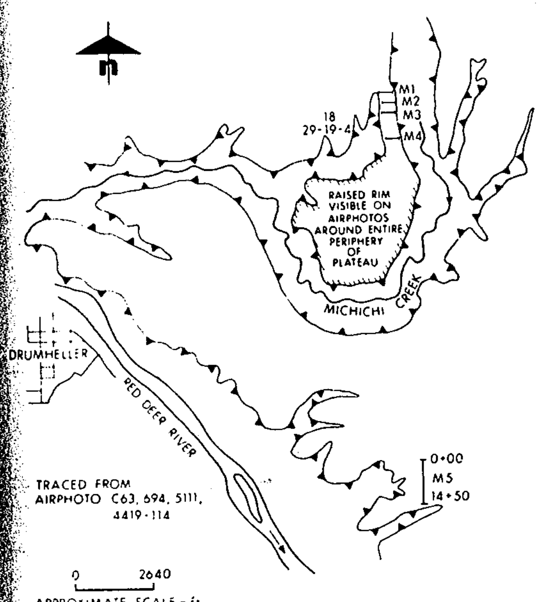

FIG. 15. Location of ground surface profiles on Michichi Creek near Redcliff, Alberta.

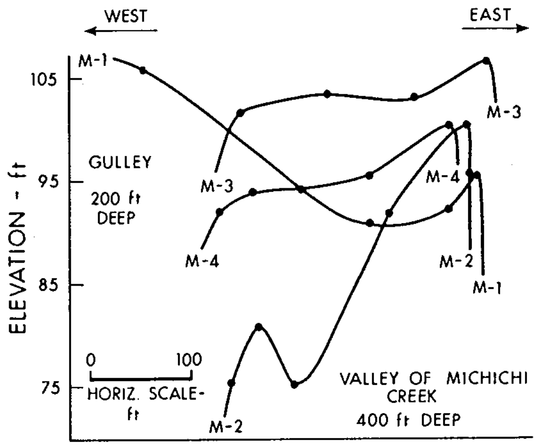

FIG. 16. Ground surface profiles at Michichi Creek, Alberta.

should be noted that the well-developed rim on the east side of the River is augmented apparently by loess deposits which decrease with distance away from the river. In all cases documented in Alberta no evidence was observed to suggest the raised rim was due to loess or alluvial deposits.

The raised valley rim often exerts a strong influence on the drainage pattern which has developed postglacially adjacent to the valley due to the low relief in the area. The features that develop along the uplands near the main valley depend largely upon the magnitude of the raised rim and include the following features. Narrow sloughs or wet depressions, distinguishable on air photos by the vegetation, are noted near and parallel to the valley walls. Gullies occur parallel but landward from the valley wall. These are generally a few hundred yards in length before they make sharp bends and join the main valley at right angles. Parallel tributaries occur which may be a development from gullying but are often further back from the valley wall and follow the main valley for some distance before entering it. Where a high raised valley rim occurs, drainage from the rim flows landward, as a sort of "backward" drainage, to tributary streams which enter the valley at widely separated points.

Figure 19 is a schematic diagram illustrating the development of drainage pattern associated with the development of a raised valley rim. It is possible that the features outlined in the previous paragraph are different time manifestations of an erosional sequence. Run off from higher areas remote from the valley would be deflected by the rim and flow parallel to the main valley for some distance before joining the main stream. These geomorphic features are visible on air photos and topographic maps. Fig. 20 illustrates gullies and parallel tributaries as visible on a topographic map.

The drainage patterns of the tributary streams are neither lithologically nor joint set controlled. This conclusion was established by an independent observational program the results of which are to be published elsewhere (Dr. A. E. Babcock, personal communication 1972).

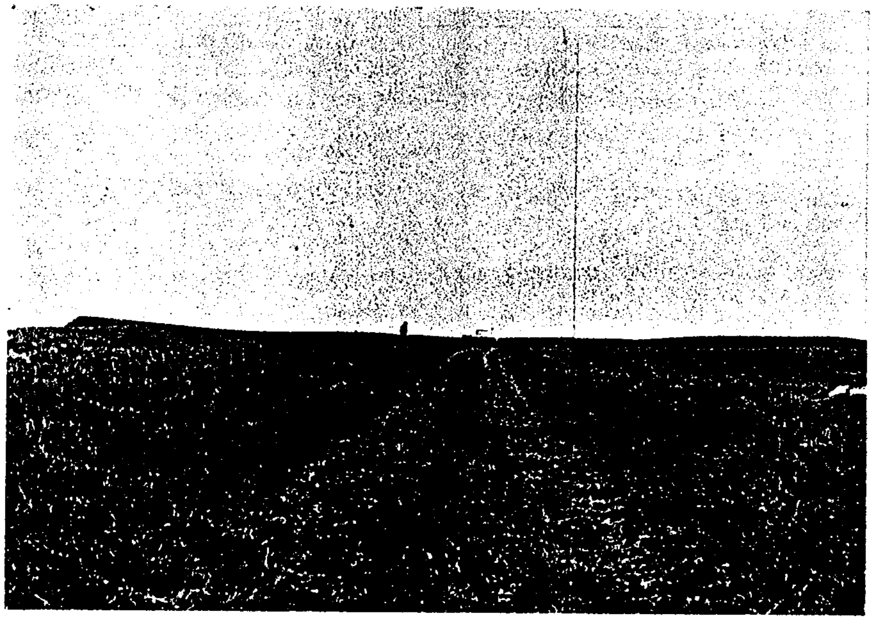

FIG. 17. Raised valley rim, Michichi Creek near Drumheller, Alberta.

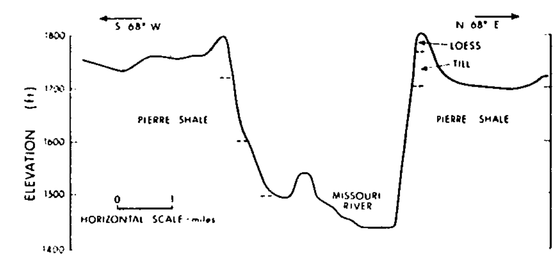

FIG. 18. Ground surface profiles on the Missouri River near Oahe Dam. (From U.S. Geol. Surv. maps.)

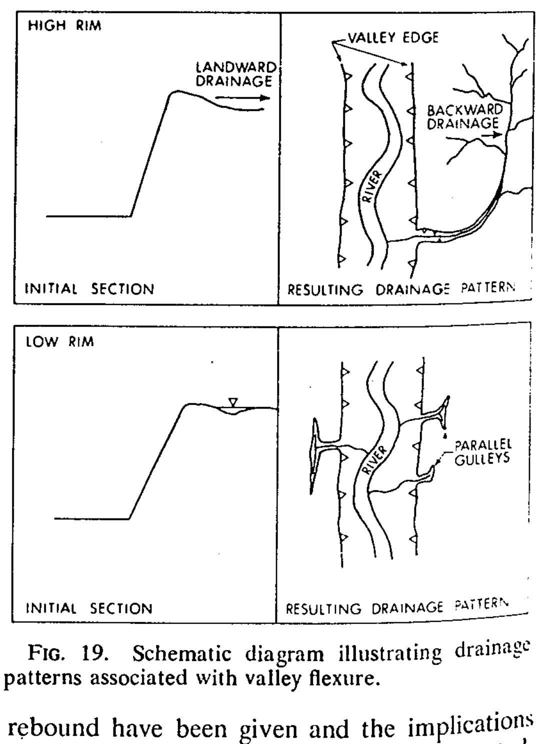

FIG. 19. Schematic diagram illustrating drainage patterns associated with valley flexure.

Summary

Valley rebound is a ubiquitous feature in areas where major river valleys are deeply incised into flat lying sedimentary rock characterized by a low modulus of elasticity. The occurrence of valley anticlines, valley flexure, and the valley rim present an interesting case where the occurrence and magnitude of natural features can be predicted by an analysis based on elastic theory). Rebound is also time dependent and continues to occur for many years after the valley is formed. The amount of rebound can be up to 10% of the valley depth though values of 3 to 5% seem to be more common.

Several typical illustrative examples of valley rebound have been given and the implications in geologic interpretation have been suggested. The gouge zones and the possible brecciation of some beds associated with rebound are of considerable concern to civil engineering pro-

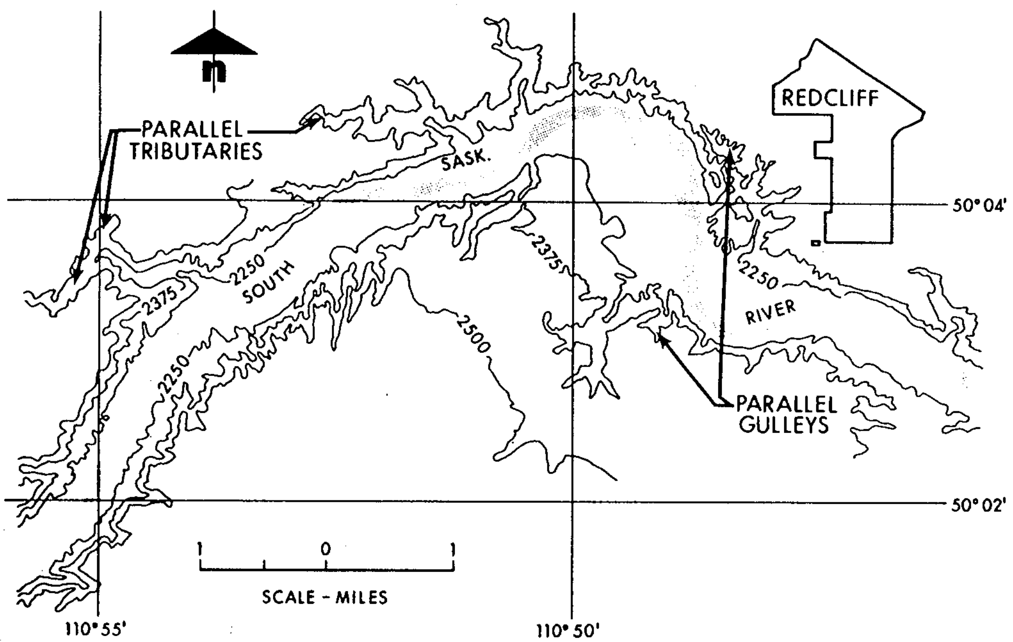

FIG. 20. Parallel drainage features near Redcliff, Alberta. Modified from N.T.S. map 72 L/2W.

cts such as earth dams, bridge foundations, d slope stability. The development of parallel llies and tributaries influence the local geo-orphology of many valleys in the study area.

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lberta Water Resources. 1968. Preliminary Engineering Report, Ardley Damsite. I and II, Development Planning Branch, Edmonton, Alberta.

ROOKER and ASSOCIATES. 1969. The Ardley Testpit. Unpubl. Rep. submitted to the Water Resources Division, Alberta Government.

CARLSON, V. A. 1966. Bedrock topography and surficial aquifers of the Edmonton District, Alberta. Res. Counc. Alberta, Rep. 66–3, Queen's Printer, Edmonton.

CHANG, C. Y. and DUNCAN, J. M. 1970. Analysis of soil movement around a deep excavation. J. Soil Mech. Found. Div., Am. Soc. Civ. Eng. **96**, no. SM5, pp. 1655–1681.

CRANDELL, D. R. 1958. Geology of the Pierre area, South Dakota. U.S. Geol. Surv., Prof. Pap. 307, 83 p.

DEJONG. 1971. Foundation displacements of multi-storey structures. Unpubl. Ph.D. thesis, Univ. Alberta, Edmonton, 251 p.

DUNCAN, J. M. and GOODMAN, R. E. 1968. Finite element analyses of slopes in jointed rock. Rep. S-68-3, Univ. Calif., Berkeley, 276 p.

GRAVENOR, C. P. and BAYROCK, L. A. 1961. Glacial deposits of Alberta. *In*: Soils in Canada, R. F. Legget (*Ed.*), R.S.C. Spec. Publ. 3, Univ. Toronto Press, pp. 33–50.

FERGUSON, H. F. 1967. Valley stress release in the Allegheny Plateau. Bull. Assoc. Eng. Geol. **4**, pp. 63–68.

FLEMING, R. W., SPENCER, G. S., and BANKS, D. C. 1970. Empirical study of behavior of clay shale slopes. I and II. U.S. Army Eng. Nuclear Cratering Group, Tech. Rep. 15, Livermore, California.

HAKE, B. G. and ADDISON, C. C. 1954. Use of bentonite beds on marker formations. *In*: Western Canada sedimentary basin and stratigraphy of the Plains of Southern Alberta, L. M. Clanke (*Ed.*), Am. Assoc. Petrol. Geol., pp. 87–97.

HVORSLEV, M. J. 1949. Subsurface exploration and sampling of soils for engineering purposes. U.S. Army

Waterways Experiment Station, Vicksburg, Mississippi, 521 p.

KNIGHT, D. K. 1963. Oahe dam: geology, embankment and cut slopes. J. Soil Mech. Found. Div., Am. Soc. Civ. Eng. **89**, no. SM2, pp. 99–125.

KUPSCH, W. O. 1962. Ice-thrust ridges in Western Canada. J. Geol. **70**, pp. 582–594.

LANE, K. S. and OCCHIPINTI, S. J. 1963. Rebound gages check movement and analysis of Garrison Dam. Proceed. Third Int. Conf. Soil Mech. Found. Eng., Zurich, **1**, pp. 402–405.

MATHESON, D. S. 1970. An air photo survey of landslides along the Pembina River. Unpubl. Int. Rep., Dep. Civ. Eng., Univ. Alberta, Edmonton, 57 p.

——— 1972. Geotechnical implications of valley rebound. Unpubl. Ph.D. Thesis, Univ. Alberta, Edmonton, 424 p.

NORRIS, D. K. 1967. Structural analysis of the Queensway Folds, Ottawa, Canada. Can. J. Earth Sci. **4**, pp. 299–321.

MORGENSTERN, N. R. and THOMSON, S. 1971. Comparative observations on the use of the Pitcher Sampler in stiff clay. Am. Soc. Testing Mater., Spec. Tech. Publ. 483, pp. 180–191.

PETERSON, R. 1954. Studies of Bearpaw Shale at a Damsite in Saskatchewan. Proceed. Am. Soc. Civ. Eng., Separate no. 476, **80**, August.

——— 1958. Rebound in the Bearpaw Shale, Western Canada. Bull. Geol. Soc. Am. **69**, pp. 1113–1124.

P.F.R.A. 1956. Preliminary soil mechanics report on Boundary Damsite 4. Soil Mech. Mater. Div., Saskatoon, Saskatchewan.

——— 1970. Soil mechanics report on Hairy Hill Damsite. Soil Mech. Mater. Div., Saskatoon, Saskatchewan.

RINGHEIM, A. S. 1964. Experience with the Bearpaw Shale at the South Saskatchewan River Dam. Trans., Eighth Int. Congr. Large Dams. Edinburgh, **1**, pp. 529–550.

SCOTT, J. S. and BROOKER, E. W. 1968. Geological and engineering aspects of Upper Cretaceous Shales in Western Canada. Geol. Surv. Can., Pap. 66–37, 75 p.

SMITH, C. K. and REDLINGER, J. F. 1953. Soil Properties of the Fort Union Shale. Proceed., Third Int. Conf. Soil Mech. Found. Eng. **1**, pp. 62–66.

TAYLOR, R. S., MATHEWS, W. H., and KUPSCH, W. O. 1964. Chapter 13 Tertiary. *In*: Geologic history of Western Canada, McCrossan, R. G. and Glaister, R. P. (*Eds.*), Alberta Assoc. Petrol. Geol., Calgary, pp. 190–200.

THOMSON, S. 1970. Riverbank stability study at the University of Alberta, Edmonton. Can. Geotech. J. 7, pp. 157–168.

U.S. Corps of Engineers. 1946. Garrison Reservoir, Missouri River Basin, North Dakota, Basis of Design, Definite Project Report. Omaha, Nebraska.

——— 1948. Oahe Dam and Reservoir, Definite Project Report, Appendix III—Geology. Omaha, Nebraska.

UNDERWOOD, L. B. 1964. Chalk foundations at four major dams in the Missouri River Basin. Trans., Eighth Int. Congr. Large Dams, Edinburgh, **1**, pp. 23–45.

UNDERWOOD, L. B., THORFINSON, S. T., and BLACK, W. T. 1964. Rebound in the redesign of Oahe Dam hydraulic structures. J. Soil. Mech. Found. Div., Am. Soc. Civ. Eng. **90**, no. SM2, pp. 65–86.

WILLIAMS, G. D. and BURK, C. F., JR. 1964. Chapter 12 Upper Cretaceous. *In*: Geologic history of Western Canada, R. G. McCrossan and R. P. Glaister (*Eds.*). Alberta Assoc. Petrol. Geol., Calgary, pp. 169–189.

ZARUBA, Q. 1956. Bulged valleys and their importance for foundations of dams. Trans., Sixth Int. Congr. Large Dams, N.Y., **4**, pp. 509–515.

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Introduction

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