THE EXPLORATION FOR MISSISSIPPIAN BURIED HILLS IN THE NORTHEASTERN WILLISTON BASIN

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ABSTRACT

In southeastern Saskatchewan, in a small portion of southwestern Manitoba and in the immediately adjacent area of North Dakota, most of the Mississippian oil fields which produce from the lower Frobisher Beds, the Alida Beds and the Tilston Beds occur in buried hills. The oil (locally accompanied by a small gas cap) has accumulated beneath the top-Mississippian unconformity and the accompanying "caprock" wherever the subcrop trend of a reservoir bed crosses a paleotopographical ridge. Accumulations in the Lodgepole (Souris Valley), upper Frobisher, Midale and Ratcliffe Beds do usually not depend on paleotopography and are therefore not discussed in this paper. Not less than 51% of all primary recoverable reserves of light Mississippian crude in southeastern Saskatchewan is trapped in buried hills, or 32.5% of all primary recoverable reserves of oil of this area. This percentage should continue to increase in the coming years as our understanding of the nature of buried hills and our methods of locating them improve.

The writer's original reason for making a study of the nature of buried hills was the lack of dependable seismic reflections. Since the unconformity at the top of the Mississippian is an old land surface, irregular, weathered and strewn with rock fragments (as known from cores), it can hardly be expected to be a good seismic reflector. Buried hills are therefore usually only evident seismically from their draping effect on overlying Jurassic horizons. A hill of 100 feet elevation over the adjoining valleys would, however, only show 32 feet of relief due to differential compaction at the base of the Jurassic. This may be too thin an interval to be easily discernible in areas of less than perfect seismic response. Seismic discoveries of buried hills have therefore been limited largely to those hills which coincide with internal Mississippian structure, such as Lost Horse Hill, Freestone, Alida and others.

A geological analysis of the nature of buried hills is possible only through a thorough understanding of the science of geomorphology. Buried hills, in contrast to structural and stratigraphic traps, were shaped by the effect of erosion (mostly running water) upon a landscape. Their present shape depends on the interaction between these erosional forces and the underlying geology. Hydrocarbon traps of this type are referred to as paleogeomorphic traps. The science of paleogeomorphology covers all geomorphic phenomena recognized in subsurface geology, which includes many features besides buried hills.

The interpretation of buried landscapes presents many problems which are still unresolved among geomorphologists, and also draws attention to a number of less well known geomorphological phenomena which are important from the paleogeomorphological point of view. There is scope for an exchange of ideas between paleogeomorphologists and geomorphologists which could greatly benefit the understanding of many geomorphic phenomena. The existence of buried landscapes of sufficient relief to lead to the trapping of oil and gas proves that many surfaces, although exposed to erosion for close to a hundred million years, did nevertheless not become "peneplains" according to the classical American geomorphological concepts of W. M. Davis. The original (pre-compaction, pre-tilt) slope of the flanks of Mississippian hills in southeastern Saskatchewan varies from 10 to 230 feet per mile. Modern stripped plains ("pediplains") in central Africa are inclined from 6 inches to 160 feet per mile, but do not show the dissection into hills of limited dimensions as seen in the buried Saskatchewan landscape. It is thus obvious that a pediplain cannot be defined by slope angle alone, if buried landscapes such as this are to be excluded from this definition.

The presence of well-developed slopes, even if only of 1 in 23, or 2°30′, argues perhaps more in favour of Walther Penck's theory of "scarp retreat" than for W. M. Davis' peneplanation through gradual flattening of slopes. The actual slopes of the flanks of these buried hills may be well in excess of 2½°; our knowledge of these slopes is, after all, limited by the well control afforded by 80-acre spacing.

An eloquent way of presenting a map of the buried Mississippian landscape in southeastern Saskatchewan is by the use of an isopach map of the overlying transgressive Lower Watrous (Spearfish) "Red Beds" of Triassic (?) age. Correlation of thin siltstone markers within this formation along a cross-section following the deepest buried valley in this area indicates that no tilting took place during depo-

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sition of the Red Beds, except along one small flexure. Pre-compaction thickness of the Red Beds can be calculated to have been an average of 47% over their present thickness.

The Red Beds isopach map shows a landscape of regular drainage features which can best be termed a "cuesta landscape". A cross-section at right angles to the strike of the ridges shows consequent drainage with a gradient of 2 feet 4 inches per mile (about as much as the Missouri River). The main ridges or "cuestas" correspond to the subcrop trends of the Tilston and the Alida Beds, at the top of which there are obviously horizons highly resistant to erosion. At the base of (north of) these escarpments lie well-developed subsequent valleys, into which flowed obsequent and resequent streams approximately parrallel to the consequent drainage. There is no evidence of closed valleys, sinkholes or other indications of Karst drainage.

The map shows other, subsidiary cuestas which represent local developments of erosion-resistant horizons. In order to determine which stratigraphic levels in any given area were resistant to erosion (ridge-forming) and which were weak (valley-forming), a frequency diagram may be used, showing how many wells encountered the Mississippian surface within any 10-foot stratigraphic interval. This necessitates very accurate correlation within the Mississippian, which is often made very difficult by the short penetration of many wells.

The buried hills all appear to rise to more or less similar height, i.e. to a "summit level" which occurs from 0 to 50 feet below the top of the Red Beds. This "Summit level" is not a dissected previous peneplain, as it was considered by W. M. Davis, but rather appears to be related to the contemporary drainage pattern. It is seen to become lower near major streams and also toward the basin.

The drainage system exhibits a certain regularity which is easily understood in terms of "quantitative geomorphology". According to the hydrophysical laws developed by R. E. Horton, the relationship between stream lengths and stream numbers of streams of succeeding orders of magnitude (order[1] representing the shortest, unbranched tributaries) approximates a geometric series. These may be plotted as straight lines on semi-log graph paper, the slope of the lines representing the "stream length ratio" and the "bifurcation ratio", respectively. The drainage system represents the interplay between these hydrophysical factors and the geological factors, such as the alternation of erosion-resistant and less resistant rocks, fault and fracture patterns, folding (if any), etc. The paleogeomorphology of southeastern Saskatchewan also exhibits some interesting features which have received very little attention to date in the geomorphological literature. Reference is made, for instance, to the phenomenon of alternating obsequent and resequent interfluve spurs, and to the oblique angle of entry of subsequent tributaries into the consequent main valley.

The recognition and understanding of all the geomorphic factors enumerated above, in combination with such geological factors as reservoir development and the internal structure of the Mississippian, are the prerequisite for a complete analysis of any portion of the area here discussed. Due to the nature of landscapes in general, no mathematically exact results may be expected from an analysis of this type, but it can certainly help to establish the approximate location of new buried hill prospects. This may then be followed by a minimal seismic program specially designed to pinpoint the prospect.