Tectonic Control on Carbonate and Evaporite Morphology: A Multicomponent Seismic Analysis

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ABSTRACT

This paper constitutes a Ph.D. thesis proposal to be carried out by the first author, the research to be supervised by the second author. It is proposed to study evaporites and carbonates, mainly of Devonian age, using both conventional seismic and multicomponent or elastic–wave data. At present, the main aim is to try to establish whether any relationship exists between tectonism and salt dissolution or reef formation. In order to undertake this we need to develop a better understanding of the underlying basement structure beneath such features. It is anticipated that data processing and modelling of the multicomponent surface seismic lines will perhaps give a better resolution of these particular morphologies and lead to a more confident interpretation than has so far been published. A brief review of previous work relating to the subject of reef formation, salt dissolution and their proposed interaction with basement structure will be given here, together with areas of possible further research.

INTRODUCTION

The Western Canadian Sedimentary Basin contains one of the best known Palaeozoic reef provinces in the world, with various depositional and diagenetic models having been published. The area is also underlain by a number of thick evaporite successions, commonly associated with the carbonate facies. However, there are still fundamental problems that are unresolved and new insights are needed to assess the validity of current hypotheses.

In other sedimentary basins, a close correlation has been observed between basement structure and depositional patterns, for example in Mesozoic rift basins of the Western Atlantic region such as Grand Banks, Newfoundland (Tankard & Welsink, 1987). A similar relationship between basin fill and basement in the Western Canada Sedimentary Basin has been postulated by numerous investigators (Sikabonyi & Rodgers, 1969; Mountjoy, 1980; and others). Clearly, knowledge of the basement structure and composition is a major factor in determining whether any such relationship may have existed.

Tectonic control over reef development in Alberta has been suggested by many workers but there has been little evidence for it apart from the arrangement of reefs along certain lineaments (Martin, 1967; Mountjoy, 1980; and others) and illustrated in figure (1). In Saskatchewan and Alberta the initiation of salt removal has been attributed to the effects of basement topography, pre–Middle Devonian highs, or Winnipegois highs due to reef build–up (DeMille, 1964; Kent, 1968; and others). It has also been suggested by Smith and Pullen (1967) that salt dissolution is partly related to basement faulting or rejuvenation

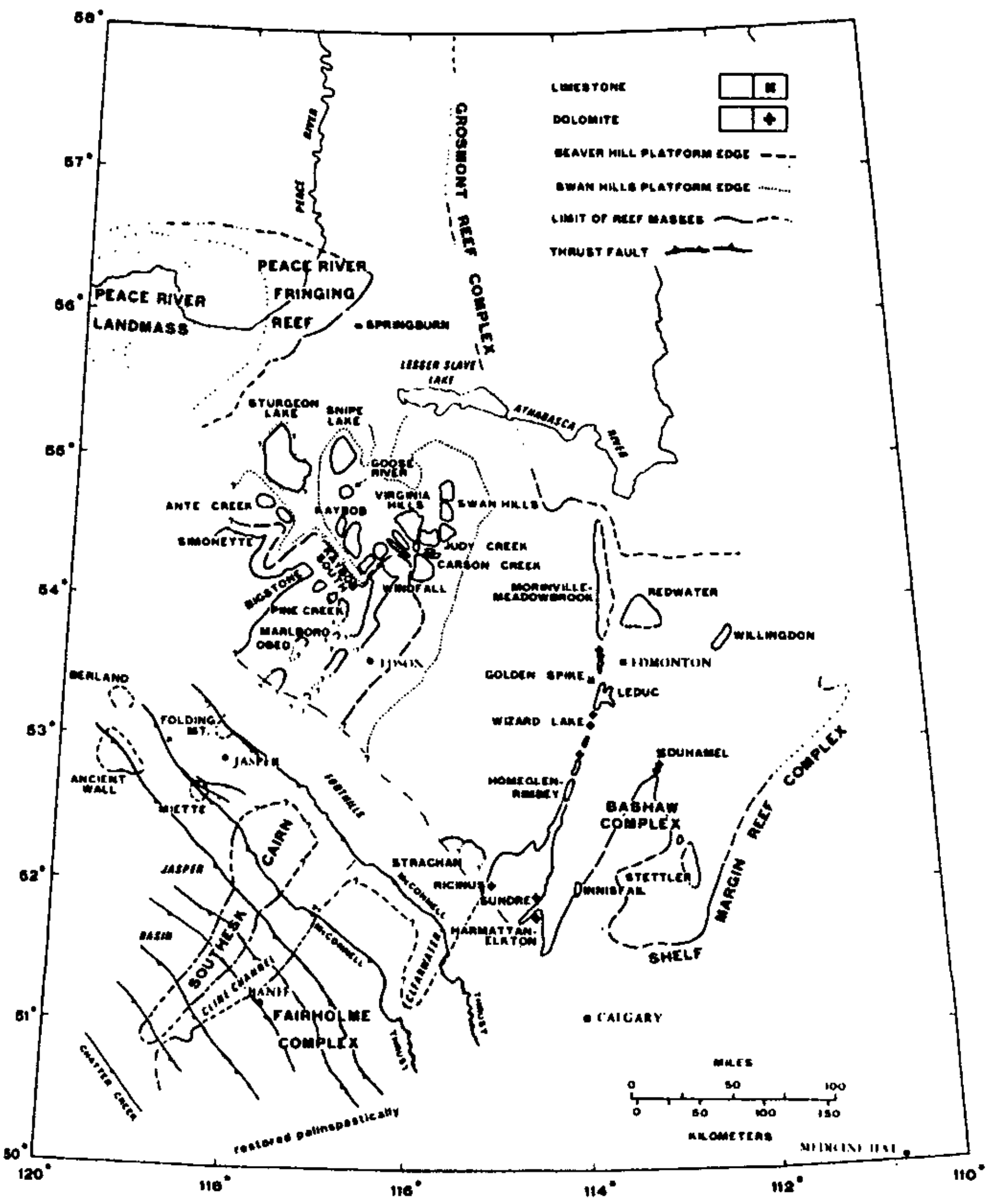

Figure (1). Map of Upper Devonian reef complexes and platforms in Alberta, with the Rocky Mountain portion palinspastically restored. (modified from Mountjoy, 1980).

of old structural basement features. The case for basement tectonics as a factor in carbonate reef sedimentation or as a salt dissolution mechanism still remains unproven, over thirty years after it was first suggested by Belyea (1955).

BASEMENT STRUCTURE

The last fifteen years have witnessed a dramatic change in several disciplines critical to basement studies. High resolution aeromagnetic and gravity data are available for much of the Western Canada Sedimentary Basin, permitting tectonic elements of the Canadian Shield to be traced in detail beneath the platformal cover.

The regmatic or orthogonal fracture system is the oldest and most pervasive tectonic regime affecting the Western Canada Basin. Numerous workers have identified the dominant fracture directions in the basement : NE – SW and NW – SE; and these form the main " pairset ". NNE – SSW and NNW – SSE forms another, less dominant, pairset. The patterns result in vertical bounding faults so as to produce a mosaic of horsts and grabens which exhibit reversals of vertical movement through geological time (Greggs & Greggs, 1989) – sometimes indicative of strike–slip motion.

DEVONIAN REEF DEVELOPMENT

There are various factors which govern carbonate build–up and reef development. Mountjoy (1980) suggests the more important are : 1) relative sea - level fluctuations; 2) amount or location of mud deposition; 3) presence or absence of skeletal accumulations and hardgrounds; and 4) positive elements in the basin.

Belyea (1955) first commented that " differential subsidence, probably controlled by lines of weakness in the basement complex, may have been the important factor in determining reef distribution " [for the Woodbend Group]. Since then numerous authors have discussed NW – SE and SW – NE trending, basement–related, structural controls on sedimentation of Upper Devonian age in the Alberta Basin. A generalized stratigraphic cross–section illustrating the nomenclature associated with Upper Devonian carbonates is shown in figure (2).

The Upper Devonian Leduc reefs form an intriguing linear, northeast - trending reef chain (fig 1). The origin of this pattern has long been disputed, with a possible cause being basement control (Mountjoy, 1980). The linear Rimbey–Leduc reef trend coincides with the Rimbey Arc in the basement (fig 3). From this close spatial correspondence arises the question of cause and effect. The same trends are also evident in the Swan Hills region. Keith (1970) describes the Kaybob reef of the Swan Hills Formation and suggests it fits into a well expressed orthogonal tectonic pattern controlled by large–scaled basement features. The Southesk–Cairn build–up margin and the Cline Channel illustrate these trends after palinspastic restoration. Viau (1987) has mapped a relationship between sedimentological patterns in the Swan Hills reef and a set of southwest–trending offsets believed to be due to faulting.

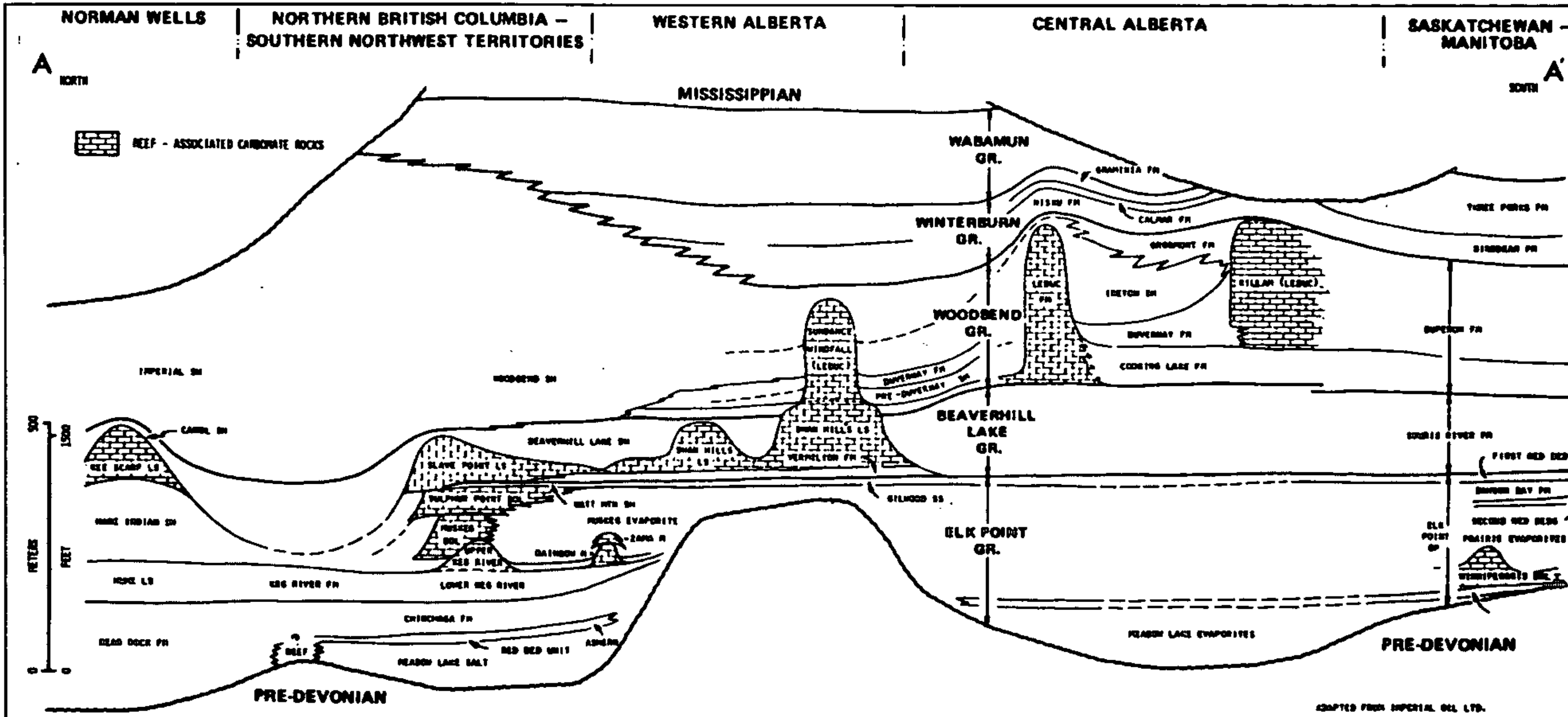

Figure (2). Generalized stratigraphic cross–section for the Devonian carbonates and evaporites of Western Canada (after Davies, 1975).

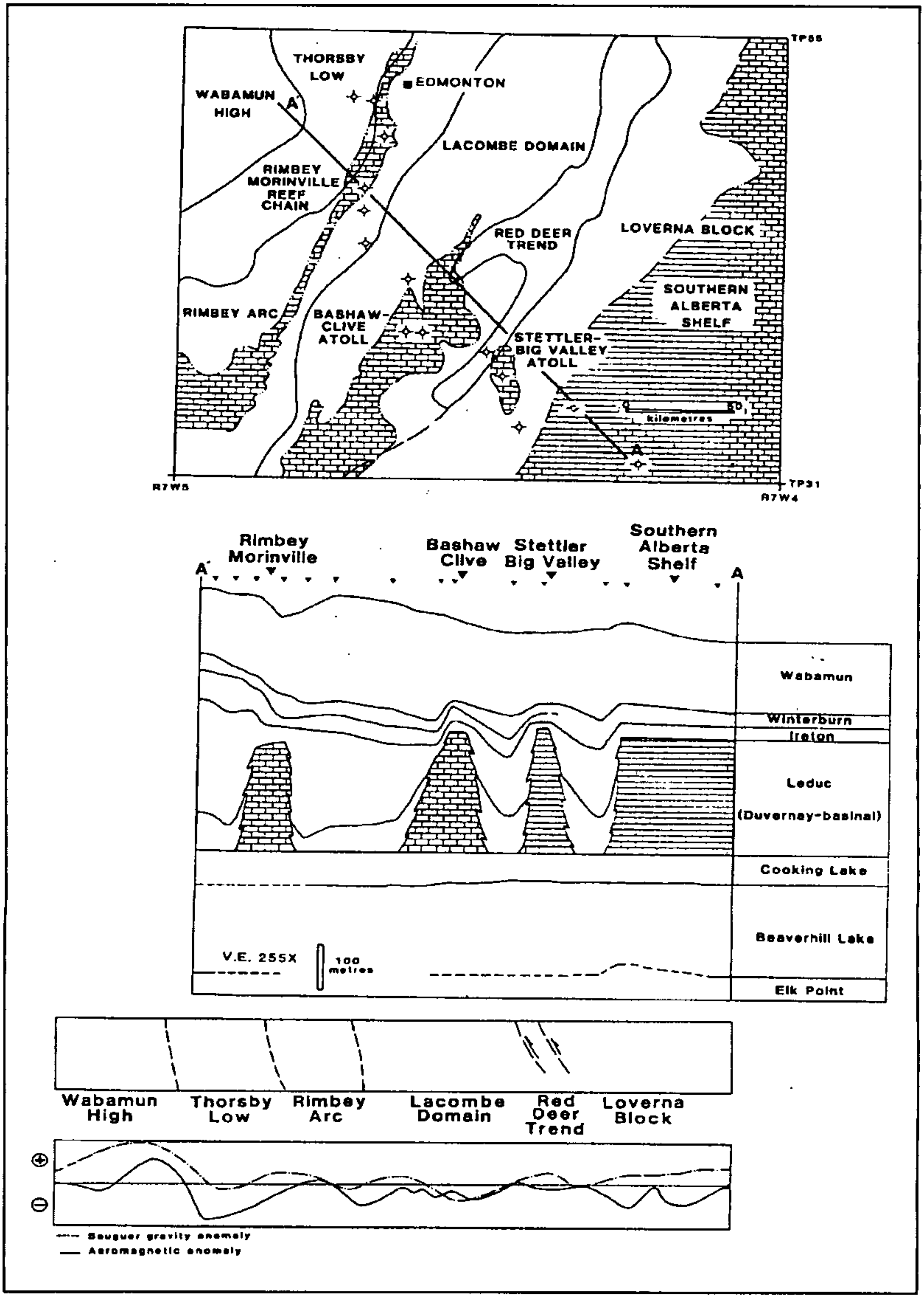

Figure (3). Diagram illustrating the close relationship between the orientation of Upper Devonian reefs and basement structure.

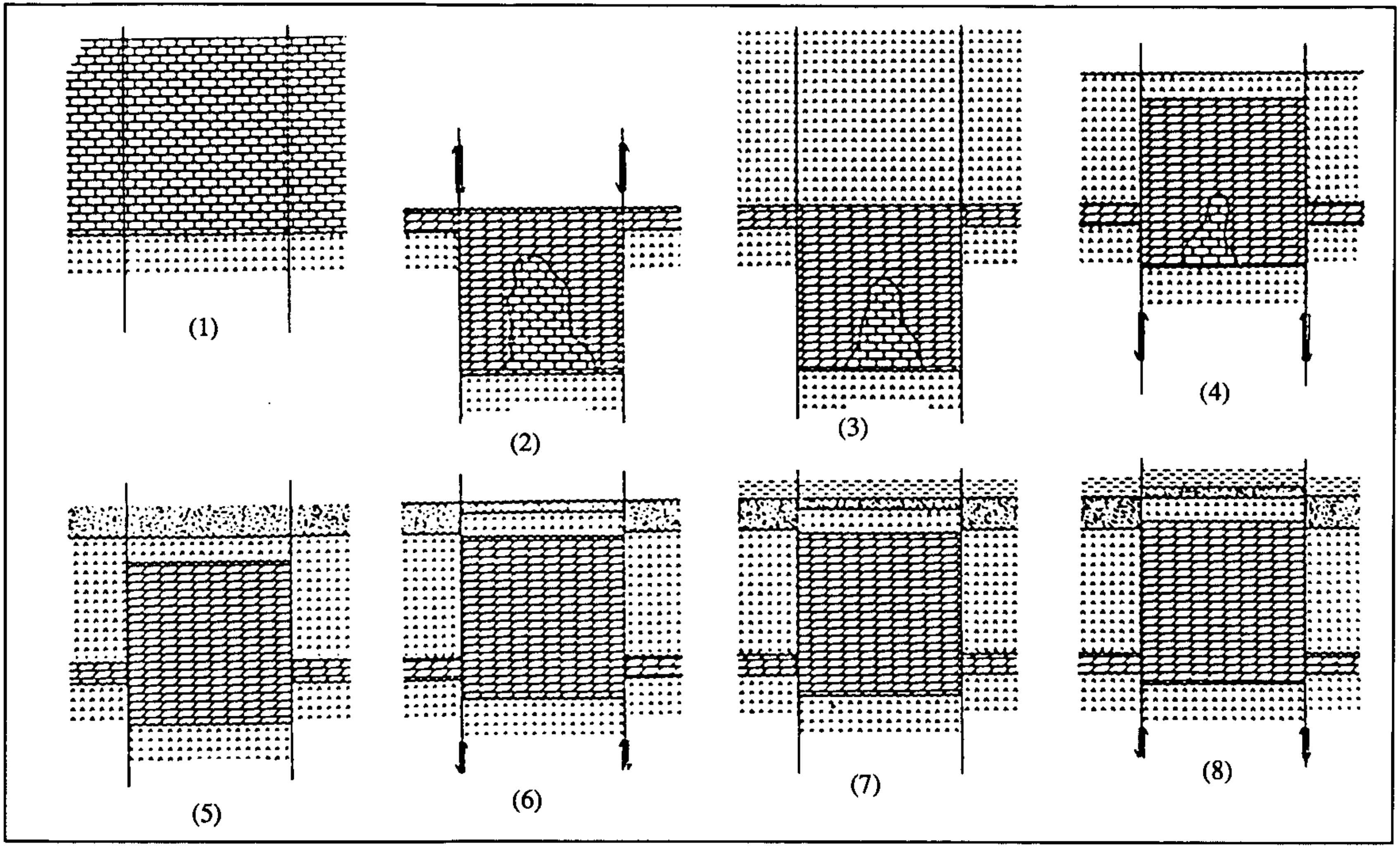

Figure (4). Greggs & Greggs' (1989) model for the sequence of structural and erosional events in the formation of a fault block (see text for explanation).

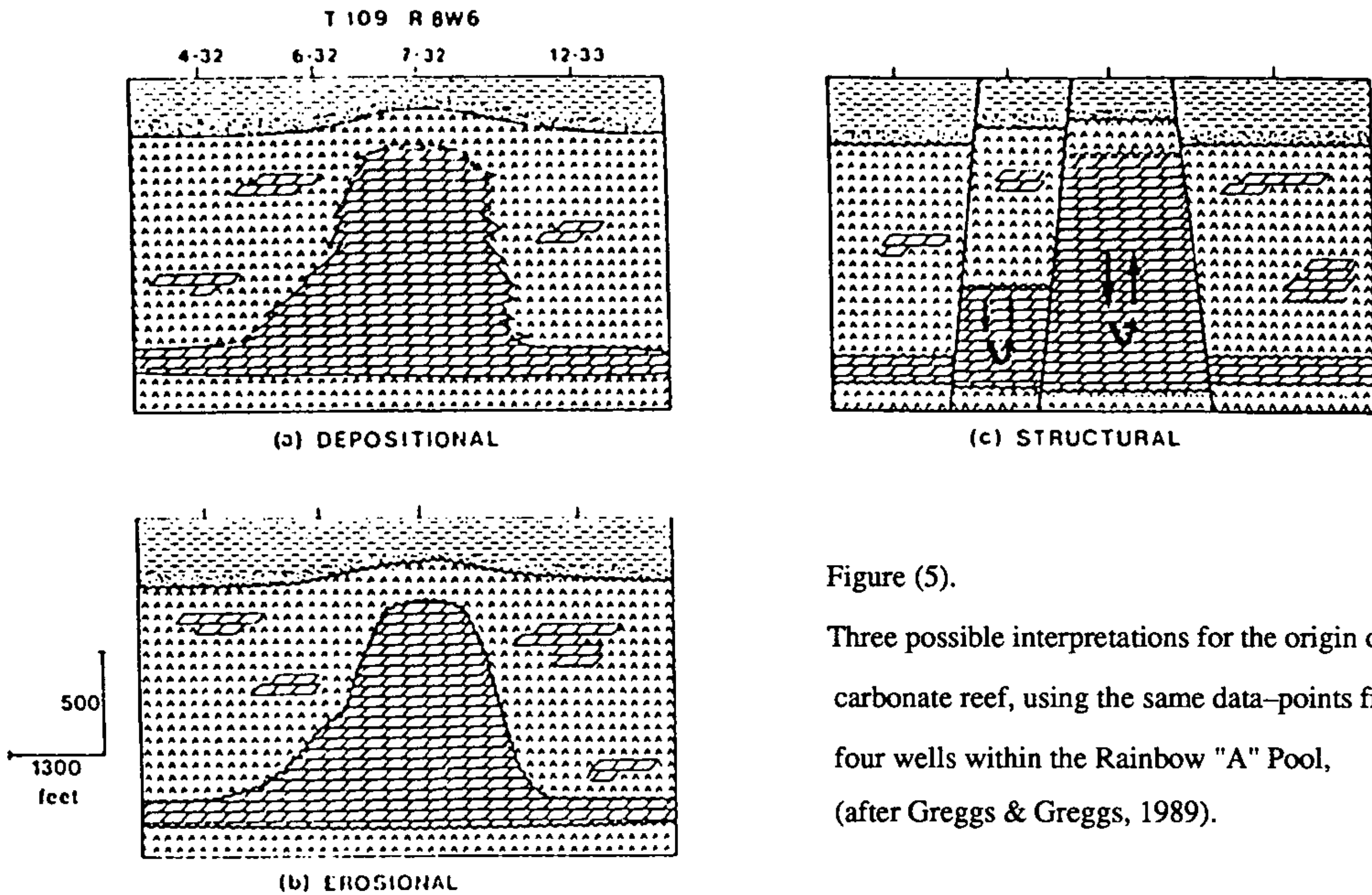

Figure (5).

Three possible interpretations for the origin of a carbonate reef, using the same data–points from four wells within the Rainbow "A" Pool, (after Greggs & Greggs, 1989).

The extreme model regarding the influence of tectonics on reef formation is provided by Greggs and Greggs (1989), illustrated by figures (4) and (5). They describe a sequence of events in the formation of a dolomitised fault block (" reef "), possessing structural relief in the subsurface, with the Devonian stratigraphic succession as present in the Rainbow Basin, N.W. Alberta (fig 4): 1) unit of limestone unconformably deposited over anhydrite; 2) extensive tectonism inducing block subsidence by pre–existing normal faults; 3) renewed marine transgression with anhydrite deposition; 4) block undergoes isostatic recovery and moves upward, accompanied by regression; 5) renewed transgression results in sand deposition (cratonic source); 6) continued isostatic recovery and block erosion; 7) and 8) are the same as 6) but with an exponentially decreasing rate of isostatic recovery. Indicators of structural deformation have been found in a large number of carbonate cores. These include fracturing (with mineralization), slickensides, stylolites and brecciation.

However, other investigators have rejected any form of tectonic control on reef development. For example, Stoakes (1988) states " Leduc reefs are located on depositional highs on the underlying Cooking Lake platform, and these highs are localized along the platform margin. This margin became established along the break–in–slope on the underlying Beaverhill Lake clinoform " (fig 2).

SALT DISSOLUTION

Much of the Western Canada Sedimentary Basin is underlain by thick Palaeozoic evaporite successions and salt dissolution collapse has long been recognised as a cause of anomalous structure; with most publications dealing with Devonian salts, especially the Elk Point and Wabamun Groups. Areas affected by salt dissolution at different levels within the Devonian have been mapped by Porter et al. (1982) – see figure (6). Collapse structures, such as the Regina - Hummingbird structure (Smith & Pullin, 1967), related brecciation and faulted zones have all been well identified.

In Saskatchewan, many workers (DeMille, 1964; Kent, 1968; and others) attributed the initiation of salt removal to the effects of basement topography, pre - Middle Devonian highs, or Winnipegosis highs due to reef build - up. Others have suggested that the solution is related to basement faulting or rejuvenation of old structural basement features. Perhaps the most difficult aspect to understand is the reason for their very localised nature. If they are associated with the movements of faults at depth, it is not easy to appreciate how they come to have the circular or sub - circular form frequently observed. Faults are linear features, and Jenyon (1986) suggests that any effects of dissolution could reasonably be expected to conform to this by having an elongate configuration. Smith and Pullen (1967) proposed one explanation, namely that they could occur at intersections of two different fault systems, where additional and more extensive fracturing may produce conduits of higher permeability for migrating waters. However, Oliver and Cowper (1983) could find no evidence of basement control on Wabamun evaporites in south–central Alberta. A later study by Anderson and Brown (1991b) on the Wabamun Formation suggested that dissolution of the salts was initiated or enhanced by : 1) the near surface exposure of the salt as a result of the erosion of the overlying Palaeozoic sediment during the Pre–Cretaceous hiatus; 2) the dissolution of the underlying Cairn salt; 3) regional faulting/fracturing during the Late Cretaceous; and 4) glaciation. It may well be that faulting during the Late Cretaceous provided the dominant trigger mechanism for dissolution in large bodies of salt, but this has yet to be proven.

As fot the timing of such structures, Oliver and Cowper (1983) concluded that salt removal from the Wabamun Group in one well in the Rumsey area occurred mainly during

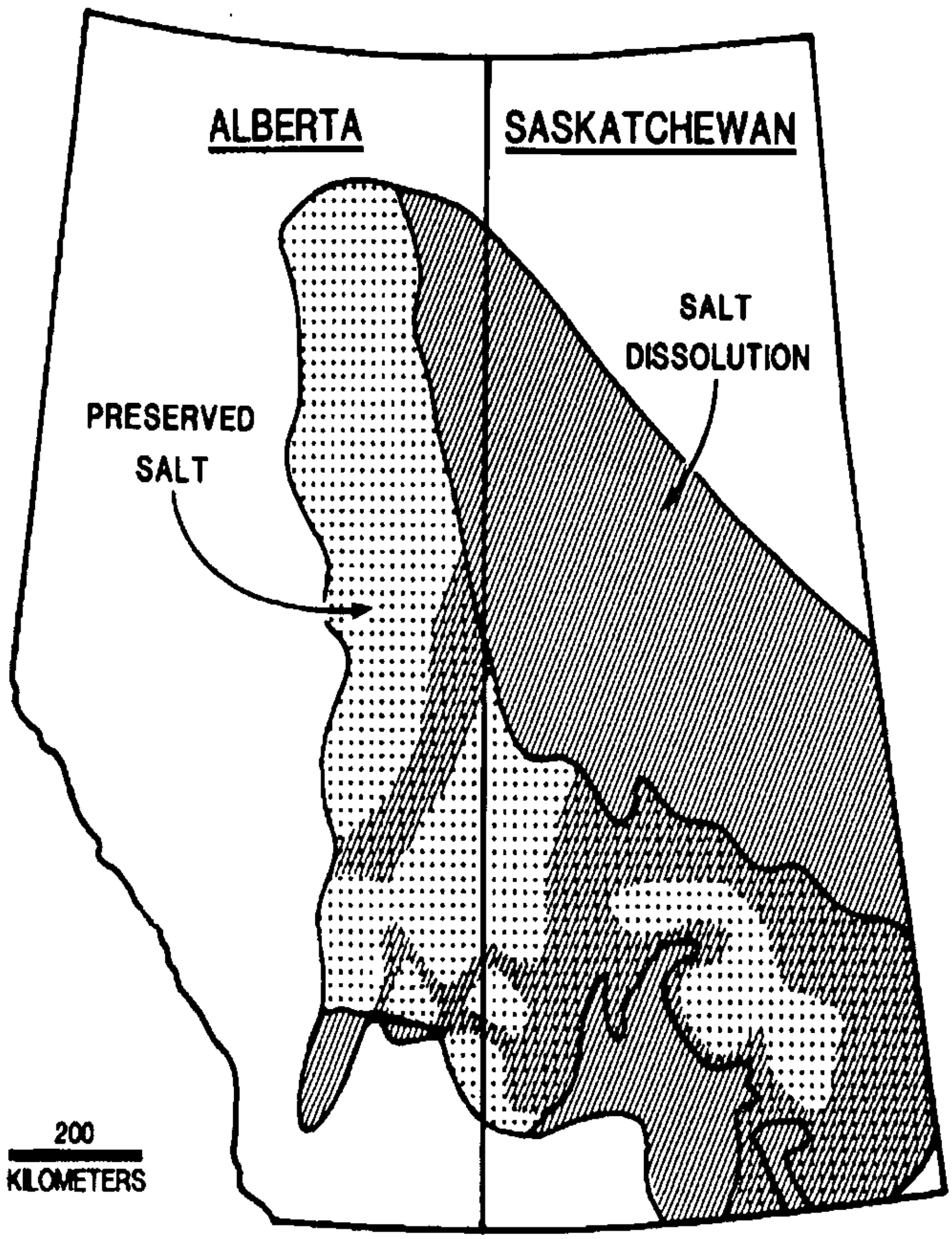

Figure (6). Map outlining the Devonian salt deposits, together with salt dissolution areas in Alberta and Saskatchewan, (modified from Porter et al, 1982).

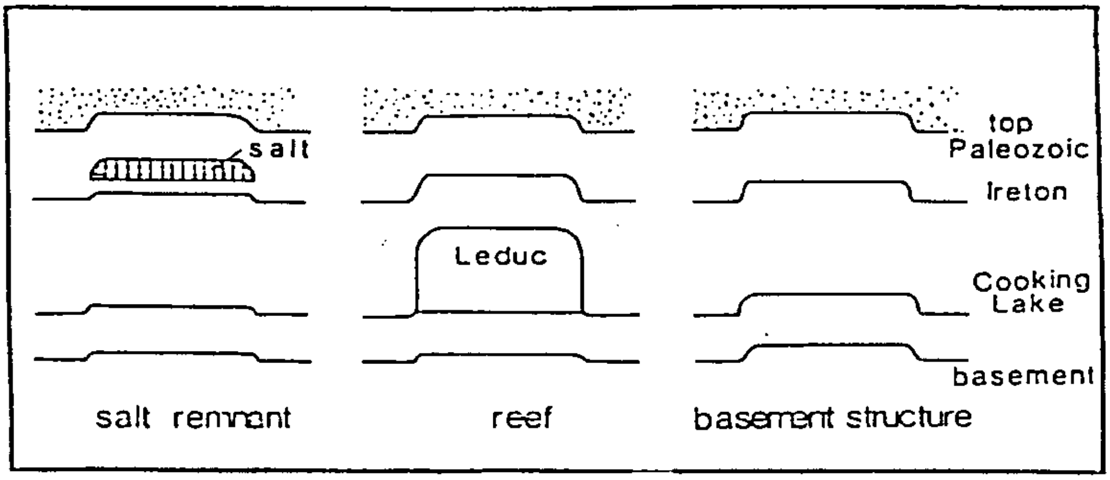

Figure (7). A remnant of salt can be misinterpreted as either reef or basement structure. The top of the Palaeozoic is time–structurally draped across salt and basement structure. The basement event is locally high as a result of pull-up and/or structural relief, (after Anderson, Brown & Hinds, 1988).

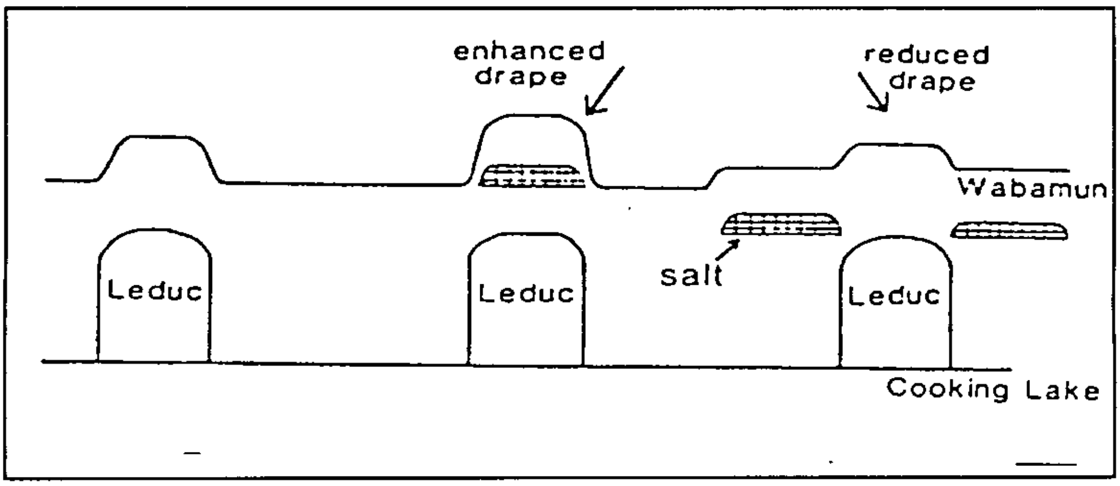

Figure (8). Wabamun salts can either degrade or enhance the seismic signature of an underlying reef, due to the drape seen at the Wabamun level (due to the compaction of reef and off–reef strata), as shown by Anderson, Brown & Hinds, 1988).

Late Cretaceous time (Colarado). On the other hand, other researchers (Hopkins, 1987; and Anderson and Brown, 1988) have suggested that the Wabamun Group appears to have been extensively dissolved more–or–less continuously throughout Mezozoic and Cenozoic time in the case of nearby areas such as Stettler.

A close relationship can be seen to exist between salt remnants and carbonate reefs. For example, Wabamun salts can either enhance or degrade the seismic signature of an underlying Leduc reef (fig 8). Recognition of geological and geophysical anomalies created by salt removal and compaction is important in the hydrocarbon exploration associated with reefs. Oliver and Cowper (1983) concluded that Wabamun salt removal was probably related to draping over topographic highs created by Leduc reefs in east –central Alberta. Figure 7 illustrates how dissolution can cause time–structural relief along both reflections that are pre–salt (velocity pull–up or push–down) and on those that are post–salt (collapse structures). In most cases, the reef and evaporite velocities are higher than the velocities in the surrounding layers, causing velocity pull-up. Where reef velocity is slower than surrounding formation velocities, velocity pull-down is observed. Such relief could be misinterpreted as indicative of either reefal or basement structure (Anderson and Brown, 1988, 1989a). Therefore, there are potential pitfalls or misinterpretations when salt features are not identified and earlier workers may have erroneously attributed the initiation of salt removal to spurious pre–Devonian relief.

PROPOSAL

The subsurface distribution of the various carbonates and evaporites across Western Canada has been mapped fairly extensively , normally from well - log data. On the other hand, the mechanisms behind the initiation and development of such features are still unclear. The present aim of this research therefore is to try to delineate the processes responsible for the formation of these structures, with an emphasis on any tectonic involvement that may be identified. For example, at present there is little direct evidence of fault displacement beneath locations where extensive dissolution has occurred. It is possible that these features are difficult to resolve since they might only have very limited displacements associated with them. Other complicating factors such as the pull–up or push–down effects of pre–salt reflections would also hinder fault identification significantly.

This research is to be largely based on the interpretation of conventional 2–D seismic sections, and to be supplemented by well–log information. In addition to this, it is anticipated that multicomponent or elastic–wave seismic lines across an area containing evaporites and carbonates will be processed and modelled with the research objectives in mind. We are also planning to investigate whether P– and S– wave sections can provide additional useful information, particularly in terms of anisotropic effects. Special processing techniques such as instantaneous attributes may also be helpful in recognising subtle features related to carbonate and evaporite formations. Instantaneous phase is a measure of the continuity of events and emphasizes coherency in a seismic section. It is therefore a very effective tool for delineating discontinuities, faults, pinchouts, angularities and events with different dip attitudes. This is mainly due to the fact that the instantaneous phase is independent of the amplitude. Instantaneous frequency processing readily lends itself to reef exploration; higher frequencies accentuate the thinner layers normally found over the reef, with respect to the surrounding layers.

The main objectives of this study can be summarized thus: 1) to examine the effects of structure on evaporite and carbonate formations; 2) to develop a better understanding of basement structure; and 3) to try and improve resolution on all of these features.

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