

Well log study and stratigraphic correlation of the Cantuar Formation, southwestern Saskatchewan

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ABSTRACT

This paper presents the results of a wireline log study on the Cantuar Formation of the Lower Cretaceous Mannville Group of southwestern Saskatchewan. The purpose is to distinguish the log characters of the sediments within this formation and provide a preliminary sedimentological and paleogeographical interpretation of the study area. About 370 wells are picked by using three major correlation methods (marker bed, unit association, and consideration of depositional environments). Ten cross sections display the stratigraphic complexity of the Cantuar incised-valley fill and interfluves. Four isopach maps reflect the valley shape, size, and progressive valley fill from the thalweg (base), through the terrace, to the edge (top). The configuration of the valley sediments of relatively low permeability sealing the permeable flanks of the Roseray-Success buttes and mesas is the major mechanism of hydrocarbon trapping in the study area.

INTRODUCTION

This study is intended to support the Ross Lake project taken on by the CREWES (Xu et. al) and to provide a geological interpretation. The study area is in Townships 11-15, Ranges 15 to 18, west of 3rd Meridian in southwestern Saskatchewan (Figure 1). About 370 wells are used for correlation and mapping. Ten cross sections tie the study together (Figure 1). Six of them are north-south oriented (N-S-1, N-S-2, N-S-3, N-S-4, N-S-5, and N-S-6), and four of them are west-east oriented (W-E-1, W-E-2, W-E-3, and W-E-4).

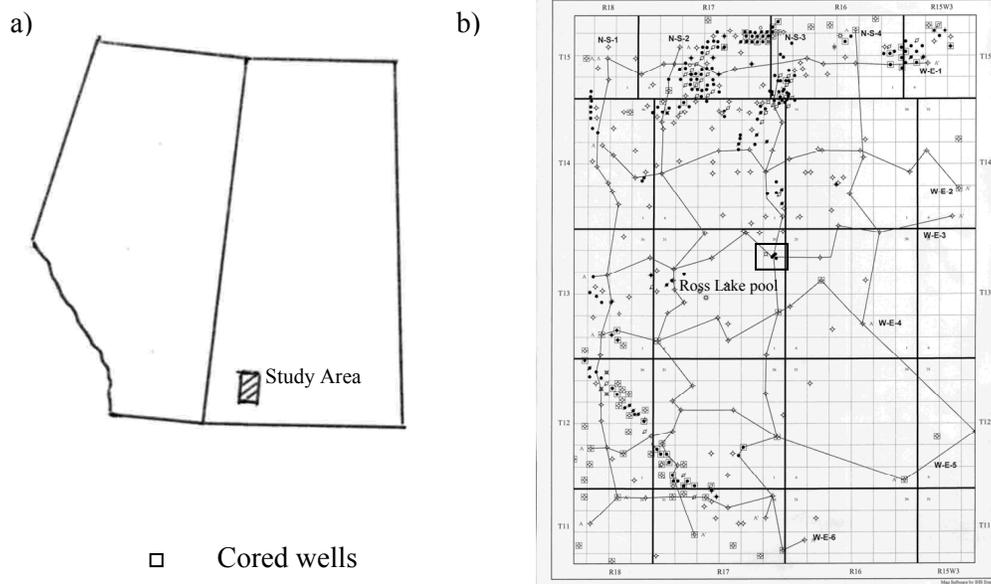


FIG. 1. Study area covers Ranges 15-18 west of the 3rd Meridian, and Townships 11-15. Cored wells and locations of 10 cross sections and Ross Lake pool are shown.

The Cantuar Formation of the Lower Cretaceous Mannville Group is the focus of this study. As the sediments of the Cantuar Formation mostly occur within ancient valley systems (Christopher, 1974), which carved into the Success Formation and the Upper Jurassic Vanguard Group (Figure 2), it is necessary in this study to investigate these older strata as well.

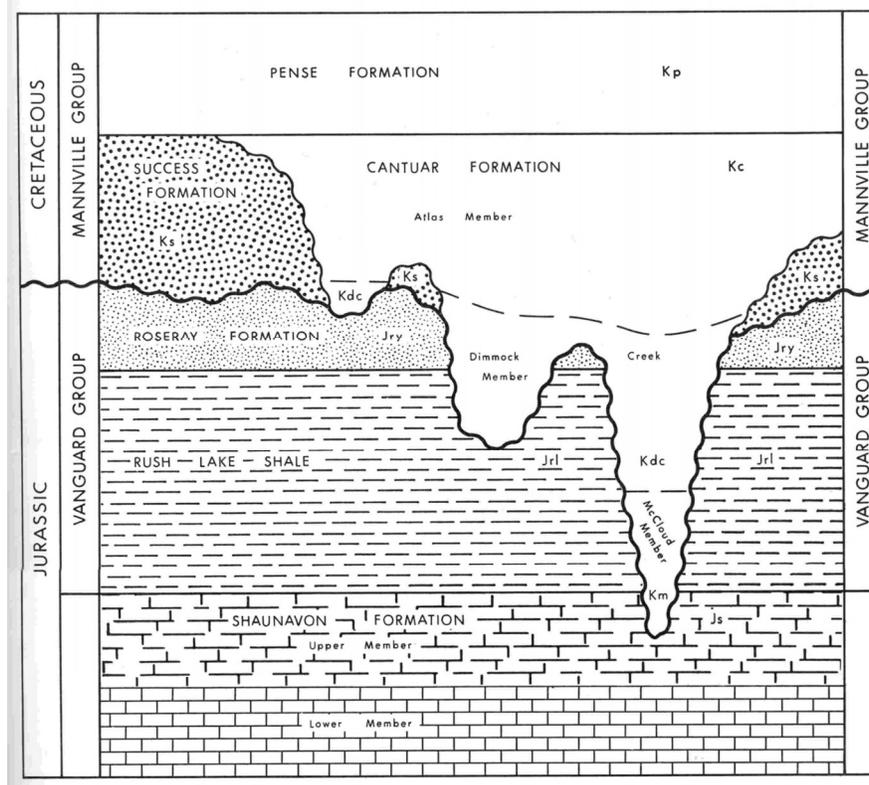


FIG. 2. Stratigraphic relationship of the formations within the Mannville Group and Vanguard Group, southwestern Saskatchewan (from Christopher, 1974).

The Vanguard Group consists of the basal Rush Lake Shale, the middle Roseray Formation, and the upper Masefield Shale in the study area. The Mannville Group is subdivided into the Success, the Cantuar, and the Pense formations. The Cantuar Formation is further subdivided into the McCloud, the Dimmock Creek, and the Atlas members (Figure 2; Christopher, 1974). Note that the Masefield Shale was not shown in this diagram by Christopher (Figure 2). We have found that the Masefield Shale is widely distributed in this study area, especially common between the Success Formation and the Roseray Formation in the interfluvial areas where it was not eroded (wells 31/01-22-015-16W/3 to 41/11-10-013-16W3 on cross section N-S-4).

TECTONIC SETTING

The tectonic elements associated with southern Saskatchewan and surrounding areas are shown in Figure 3. The Williston Basin is an ellipsoidal depression centred in North

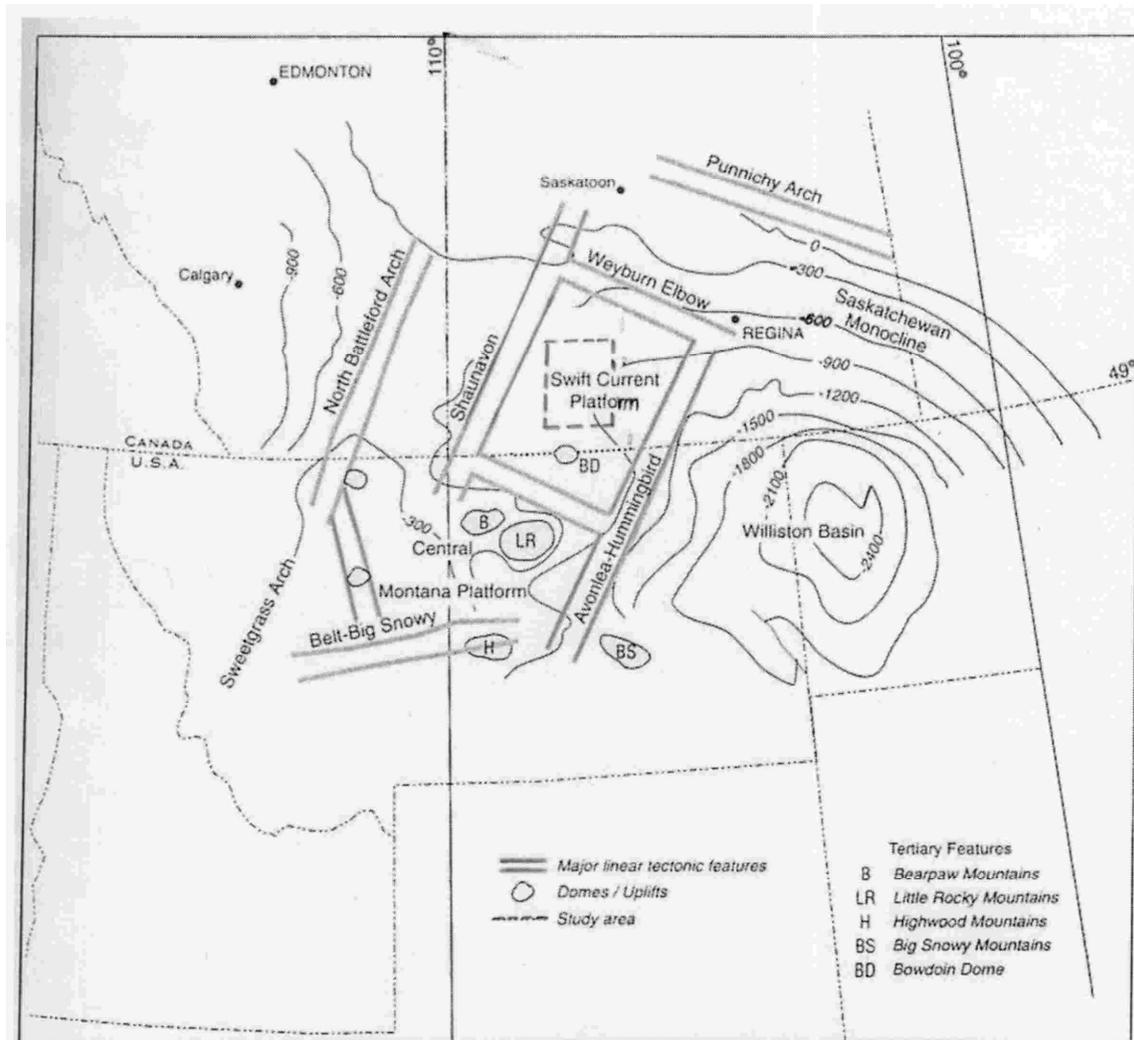


FIG. 3. Structural features in southwestern Saskatchewan and surrounding area (from Kent and Christopher, 1994).

Dakota and forms the southern extremity of the Western Canadian Sedimentary Basin. It extends into southwestern Manitoba and across southern Saskatchewan as a broad southwest-plunging trough and is bordered by the Sioux Arch to the east, the Sweetgrass Arch to the west, and the Punnichy Arch fronting the Saskatchewan Monocline to the north. The eastern portion of the Sweetgrass Arch is represented by the Swift Current Platform of southwestern Saskatchewan and the Central Montana Platform (Kent and Christopher, 1994). During the Hauterivian to Barremian (Early Cretaceous), probably due to the emplacement of the anorogenic granites (Collerson and Lewry, 1985) in the basement rocks causing thermal arching of the crustal rocks (Klein and Hsui, 1987), the Swift Current Platform and Sweetgrass Arch underwent uplift and dissection during which time the Cantuar valleys were cut. During the Albian, tectonic relaxation led to subsidence and burial of the Sweetgrass Arch (Kent and Christopher, 1994), represented by the incised valley-fill of the Cantuar Formation and subsequent blanket marine deposits of the Pense Formation.

STRATIGRAPHIC HISTORY

The Mannville sedimentary basin in Saskatchewan was activated by a Late Jurassic to Barremian reorganization of the marine Jurassic setting centred on the Williston Basin. Uplift of the Swift Current Platform (Kent and Christopher, 1994) in southwestern Saskatchewan controlled the Mannville sedimentary pattern, which was woven by an interplay of marine, estuarine and fluvial agents acting in a setting controlled by paleotopographic relief and eustatic and tectonic changes in relative sea-levels. Sediments came from local landforms, the Precambrian Shield, and from rising volcanic uplands of the Rocky Mountain geosyncline of western Montana (Christopher, 1997).

During the Middle Jurassic, the Swift Current Platform lay at the foot of the Shaunavon monocline, which rose to the west onto the Sweetgrass Arch of Alberta (Figure 3). The platform began to rise during the Oxfordian (Late Jurassic) and maintained a southeasterly tilt towards the Williston Basin centre (Christopher, 1984b). The regional geomorphic expression became one of a southward-sloping, structural plain, low in relief and patterned by widely spaced, easterly oriented cuestas on strata dipping toward the south. The lower unit of the Success Formation was laid down in the low-lying areas and is represented by shaly, sand-poor facies deposited in shallow-marine environments. Uplift in the source region to the north, accompanied by steepening gradients across southern Saskatchewan, rejuvenated the drainage system. The streams associated with the upper unit of the Success Formation drainage grew larger and braided forms. Sediments of this unit were characterized by a blanket of medium and coarse-grained cross-bedded sandstone, which were deposited on a widespread braid plain (Leckie et al., 1997).

Hauterivian to Barremian uplift of the Swift Current Platform (Kent and Christopher, 1994) led to re-organization of the Success terrain. Deep fluvial incision caused the formation of large valleys (Schumm, 1993) radiated from the upland (Figure 4). The valleys were progressively infilled by onlapping sediments of the McCloud, Dimmock Creek, and Atlas members of the Cantuar Formation (Christopher, 1974; Leckie et al., 1997). The McCloud Member occupies the thalweg of these valleys and is composed of quartzose sandstone, shale, and siltstone deposited within high-sinuosity meandering belts and floodplain environments. The Dimmock Creek Member infills much of the remainder of the valleys with shale, coal and feldspathic-lithic sandstone deposited within a general meander belt setting. The Atlas Member overlies the Dimmock Creek Member, progressively infilling the Cantuar valleys. It includes thick sandstone, shale, and coal all deposited within a general meander belt setting.

The Albian Pense Formation represents deposits associated with marine inundation of the Cantuar Formation valley-fill and the weathered interfluvial/cuesta deposits of the Success Formation. This formation is characterized by grey and black shale and thin bioturbated and wave-rippled sandstone deposited within offshore and shoreface environments (Wallace-Dudley et al., 1998).

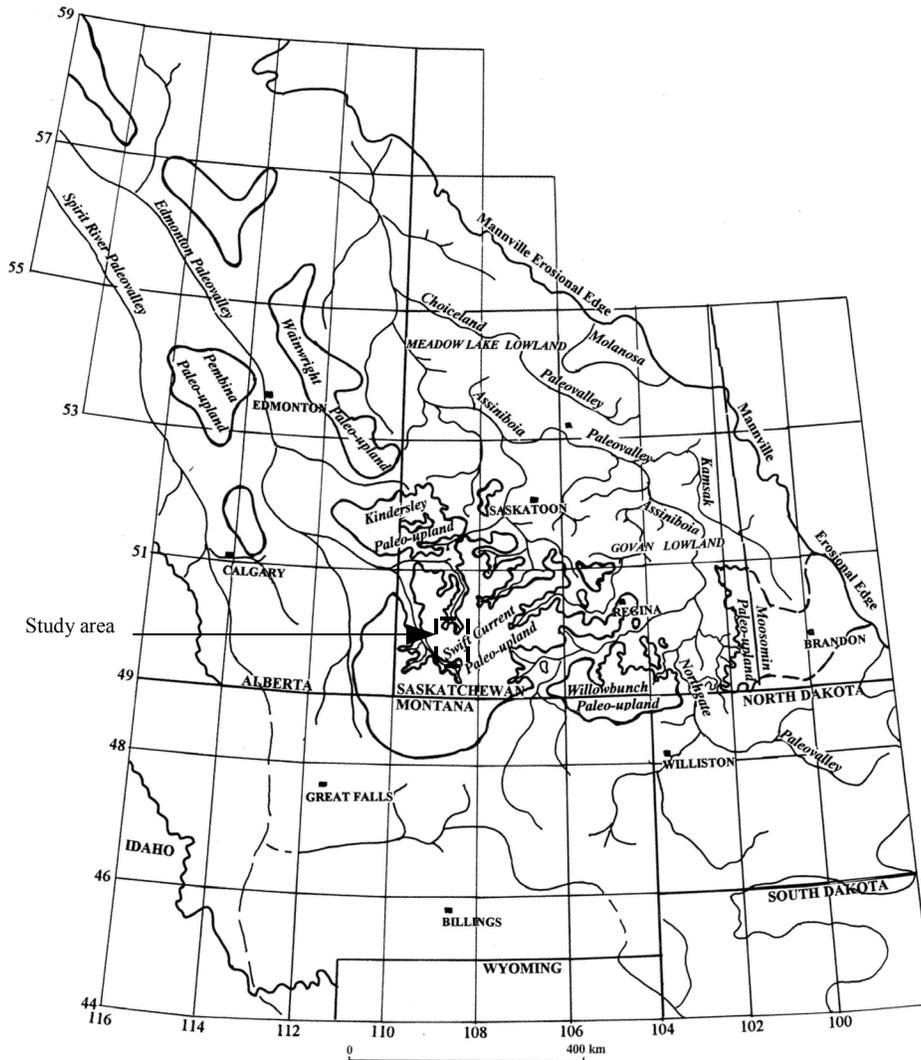


FIG. 4. Pre-Mannville drainage system of the Northern Western Interior Basin of Canada and the United States (from Christopher, 1997).

LOG CHARACTERS

Most of the formations and members in the study area have differentiable log responses although the stratigraphic relationships are very complex. Some of the log characters are constant, some are very variable, and some have not been identified in this study and will possibly be resolved by core-log integration.

Rush Lake Shale

The Rush Lake Shale is characterized by calcareous shale, calcareous mudstone and marlstone. It is often presented as an indented shaly unit on the gamma-ray log and a straight line on the SP log (Figure 5). In comparison to the Masfield Shale, the Rush Lake Shale has lower amplitudes on the gamma-ray and sonic logs (Figure 5). It is mostly overlain by the porous Roseray Formation and forms a distinct surface on the logs between these two units, which makes it simple to separate them.

Roseray Formation

The Roseray Formation is dominated by quartzose sandstone that is fine-grained and permeable. Internally, the formation is composed of several units. On the geophysical logs (Figure 5), it is best delineated by the gamma-ray and sonic curves on which it is expressed as pronounced, positive deflections reflecting the porous, well sorted sandstones. In some cases, these curves are indented by thin, strong responses of positive deflections on the sonic signature resulting from the calcite-cemented pavements that separate the permeable sandstones (Figure 5). On the SP curves, the porous sandstones are expressed as an outstanding cylindrical shape with higher amplitude than the above Success and Cantuar formations. On the resistivity log suites, the porous character is shown as wide separation between the shallow and deep induction curves.

The Roseray Formation is commonly overlain by the Masefield Shale, which forms an extremely easily identified cylindrical shape on gamma-ray, sonic, SP, and resistivity logs (Figure 5). This prominent log response is formed due to the dramatic change of lithology from very porous sandstone to highly shaly mudstone or shale.

In the cases where the Roseray Formation is overlain by the sandy Success Formation sandstone, it's more challenging to distinguish them on logs. But these formations are still differentiable by the decrease in gamma-ray API units and increase in sonic interval transit time of the Roseray Formation in response to the lower amount of clay (Well 01/15-22-014-18W/3 on cross section W-E-2).

The Roseray Formation may be in direct contact with the Dimmock Creek Member or the Atlas Member although it's not very common. The dramatic lithologic difference permits the surface to be identified readily from the log suites (well 01/10-16-012-15W/3 on cross section W-E-5).

Masefield Shale

The Masefield Formation is largely shale. It is largely truncated under the Mannville Group while a uniform geophysical log signature (Figure 5) is retained in the study area similar to, but with higher amplitudes than that of the Rush Lake Shale. The readily identified cylindrical shape on the log suites can be used as a correlation marker in the study area although the thickness is greatly variable.

The Masefield Shale is mostly overlain by the Success Formation in the interfluvial areas where it is not eroded by a valley incision. This association is present on all of the ten cross sections and shows a similar log pattern to that of the association between the Masefield Shale and the Roseray Formation. The sand-shale-sand lithologic association from the Roseray, through the Masefield, to the Success Formation constitutes a prominent log pattern and forms a general criterion for the stratigraphic correlation of the interfluvial areas.

It is not surprising to find that the Masefield Shale is overlain by the Dimmock Creek or the Atlas members where the Success Member is absent, possibly due to post-Success erosion. In these cases, it is not easy to differentiate the Masefield Shale and the above units on the gamma-ray log since both of them are largely shaly and have similar API

units (Well 11/13-35-013-17W3 on cross section W-E-3). But the Masefield Shale can be easily distinguished from the above formations on the sonic and resistivity logs, which show obvious amplitude changes (Well 11/13-35-013-17W3 on cross section W-E-3).

Success Formation

The Success Formation is composed of kaolin-cemented quartzose sandstone and siltstone deposited on a widespread braidplain. It overlies the Vanguard Group on a low and broad relief unconformity, and is truncated by the high-relief pre-Cantuar unconformity. On the logs, the Success Formation is generally expressed as a porous unit, which is identifiable from the formations below and above.

The Success Formation constitutes the top strata of the cuestas/interfluvies, and is commonly overlain by the Atlas Member, which represents the final stage of the Cantuar valley fill and blankets most of the study area. On the gamma-ray and sonic, or the SP and resistivity log suites, the Success Formation is conveniently differentiated as a porous unit from the Atlas Member, which is much shalier (Wells 41/12-20-012-17W/3 to 01/06-01-012-16W3 on cross section W-E-5).

The Success Formation is directly overlain by the Pense Formation locally where the paleo-upland was so high that it remained subaerially exposed during the Atlas deposition and finally overlapped during the Pense sea inundation. In this case, the sandy Success Formation and the above marine shale are readily differentiated from each other (Well 31/12-13-014-17W3 on cross section N-S-3).

McCloud Member

The McCloud Member comprises an upper coaly mudstone and a lower unit of two or more quartzose sandstones. It is characterized as a “d” shape on the SP logs, which reflects the bipartite lithologic composition (Figure 5).

The McCloud Member is deposited within the deepest part of the Cantuar Valley, and is commonly underlain by the Rush Lake Shale and overlain by the Dimmock Creek Member. The basal contact is clearly shown on the gamma-ray, SP, sonic, and resistivity logs while the upper contact is somewhat gradational. With careful observation, the coaly bed composing the upper half of the member can be used to define the unit on geophysical logs. This shale layer can be recognized by its extremely high amplitude on sonic and resistivity logs resulting from the coal (Cant, 1992) in comparison with the adjacent formations (Figure 5). It also has a subtle response on the SP log, which is easily missed without careful study.

Dimmock Creek Member and Atlas Member

The Dimmock Creek Member and Atlas Member are characterized by muddy sandstone and sandy mudstone. They are differentiated largely by their internal stratigraphy, rather than by their components (Christopher, 1974), which makes it difficult to distinguish them on logs (Figure 5). In this study, the pick between these two members is somewhat subjective, and is placed at a shaly layer around the middle of the unit, dividing the unit into two sandstone-mudstone interbedded parts. The upward fining successions, which characterize fluvial point bar deposits, are well displayed within both

the Atlas and Dimmock Creek members on the gamma-ray log of well 01/15-22-012-18W3 (Cross section N-S-1). In some cases, this character is not so obvious, which resulted from the frequent mudstone interbeds.

The top of the Atlas Member is defined by the transition from fluvial to marine units, which is readily identified on the gamma-ray and sonic logs of all the wells in the study area. It is noteworthy that there is a positive deflection on the SP logs right above the Cantuar-Pense contact from the majority of the wells (Figure 5). It may be interpreted as a transgressive lag.

Pense Formation

The Pense Formation is composed of several coarsening-upward units, each of which comprises basal shale, middle siltstone and upper quartzose sandstone. On the geophysical logs, they are recognized by the upward expanding positive deflections of the SP and resistivity logs.

The Cantuar Marker (Cumming and Francis, 1957), which occurs several metres above the base of the Pense Formation, is a 1 to 2 metres thick siltstone or sandstone. It is readily identified on the gamma-ray, SP, sonic, and resistivity logs, and is used as the datum of the cross sections in this study. Note that the amplitude of this marker is relatively low, which makes it necessary to identify it by the log suites, rather than by a single log. An obvious “ \exists ” shape on the SP logs (Figure 5), which is composed of the upper sandstone, the Cantuar Marker, and the basal sandstone, helps to locate the Cantuar Marker promptly.

The Pense Formation is beyond the focus of this study, and only the basal portion is shown on the cross sections.

CROSS-SECTIONS

Ten cross sections are studied. Only part of the cross section W-E-1 is shown in this report because of their extreme length (Figure 6). Two types of log suites (gamma-ray-sonic suite and SP-induction resistivity suite) are chosen for stratigraphic correlation. The major correlation methods include marker beds, unit association correlation, and consideration of the regional depositional environment.

Correlation Methods

Marker bed correlation is the most widely used and reliable correlation technique even if the lithology or origins of the beds are not known. In this study, the Cantuar Marker is found in every well without exception. It was formed after the Cantuar valley fill, thus is an ideal datum to demonstrate the valley topography on cross sections. The Masefield Shale is also used as a marker because of its readily identified log character, but it's not qualified as a datum due to its great thickness variation across the study area. It is also absent in many wells probably because of erosion, which limits its applicability.

“Unit association correlation” is named by the authors in this study, which is referred to studying several adjacent stratigraphic units as a whole, identifying them in a single well or correlating them between wells. This correlation method is widely used in this

study and found to be very effective. A typical example is the association of the porous sandstone of the Roseray Formation, the overlying Masefield Shale, and the upper porous Success sandstone, which forms a readily identified and reliable “ Γ ” shape on the gamma-ray logs. Another good example is the “ Ξ ” shape on the SP logs, which is composed of the Cantuar Marker and the adjacent strata.

Another significant approach is to consider the general depositional environment during log correlations. To be specific in this study, intra-correlation of the Cantuar members requires the section to remain in the valley trend. Conversely, correlation of the Success and Roseray formations demands that the lines of section stay on the interfluves. The usefulness of the approach in this area results from the configuration of the sub-Cantuar unconformity, which controls the distribution and general morphology of the Cantuar strata.

It must be emphasized that the most effective way is to integrate these approaches during the process of log correlation.

Each of the ten cross sections is described individually in the following paragraphs. The presence of the Dimmock Creek Member is used as the major criterion of valley identification.

Cross Section N-S-1

This cross section is characterized by the great morphological variations, which resulted from the three prominent valley incisions located at wells 01/01-15-014-18W3, 01/16-22-013-18W3, and 01/15-22-012-18W3. The second location (well 01/16-22-013-18W3) represents the deepest portion of the paleovalley in this study area, indicated by the presence of the McCloud Member, which is restricted within the thalweg (base) of the valley. The valley cut into the Rush Lake Shale at all of the three locations.

On the interfluves, the Success, Masefield Shale and Roseray formations constitute the major strata. The Masefield Shale may also be absent probably eroded by the Success channel incision.

Cross Section N-S-2

This cross section has characteristics similar to cross section N-S-1, as it is close and parallel to the latter. The deepest part of the valley is located at well 41/01-30-013-17W3 while the association of the Roseray, Masefield, and Success formations is present on most of the interfluves.

Cross Section N-S-3

This north south oriented cross section divided the study area into two halves. Well 11/14-25-013-17W3 has oil production from the Roseray Formation. From the logs of this well it can be inferred that the upper half of the sandstone is saturated with oil, which is identified on the resistivity log by the right deflection. The oil-water contact is very clear at about 1162 m.

Cross Section N-S-4

Wells on this cross section are mainly located on the interfluves, which is composed of the Roseray, Masefield, and Success formations. The thicknesses of the Success and Masefield Shale are variable, but are present at most wells. It also can be observed that the Success Formation is directly overlain by the Pense Formation in some well logs (wells 31/01-22-015-16W3 and 21/07-22-014-16W3).

Cross Section W-E-1

As to the Cantuar-valley, this cross section only occupies the interfluves without intersecting with the valley. The morphological relief present on the logs is mostly caused by the Success channel incision, which shouldn't be confused with the profound regional Cantuar paleovalley. It is noteworthy that the Dimmock Creek Member as the valley symbol is not present in any well on this cross section.

Cross Section W-E-2

On this cross section, only well 01/05-23-014-18W3 is located within the Cantuar valley while the rest are all on the interfluves. The standard “∩” shape on the gamma-ray composed of the Roseray, Masefield, and Success formations characterizes the right half of the cross section.

Cross Section W-E-3

This cross section can be divided into two parts by the morphology. The left half is characterized by the Cantuar valley fill while the right half is characterized by the interfluvial deposits.

Cross Section W-E-4

This cross section is characterized by the morphology of valley-interfluve-valley-interfluve. In comparison to cross section W-E-3, the topographic relief is relatively small, which is related to the edge of the trunk valley.

Cross Section W-E-5

Contrary to cross section W-E-4, cross section W-E-5 is composed of interfluve-valley-interfluve-valley. It indicates that the Cantuar valley extends eastward outside of the study area.

Cross Section W-E-6

This cross section presents a typical interfluvial characteristic except one well in the middle (well 01/11-33-011-17W3).

ISOPACH MAPS

Four isopach maps are generated on the basis of the log correlation of about 370 wells in the study area. The widening-upward trend (Figures 7, 8, and 9) reflects the progressive valley fill from the thalweg (base), through the terrace, to the edge (top) of the valley.

Isopach Map of the McCloud Member (Figure 7)

The McCloud Member is restricted within the thalweg of the Cantuar valley, which occupies part of the Ranges 17 and 18, Township 13. The valley extends west to northwest. The width is up to 5 kilometers, and the thickness is up to 20 metres.

Isopach Map of the Dimmock Creek Member (Figure 8)

It is shown that the Dimmock Creek Member is distributed much more widely than the McCloud Member. The trunk valley extended in the northwest direction, crossing the centre of the study area. The width is up to 10 kilometers, and the thickness is up to 32 metres. A branch valley located at the southwestern corner of the study area is approximately parallel to the trunk valley. The width is up to 5 kilometers, and the thickness is up to 25 metres.

Isopach Map of the Atlas Member (Figure 9)

The Atlas Member covers most of the study area except a portion of Ranges 16 and 17, Township 14. It thickens to the west, which corresponds to the location of the valley. Both Christopher (1974) and Leckie et al. (1997) interpret this member as part of the Cantuar-valley fill, and both of them described that the Atlas Member covers the majority (over 90 percent) of their study areas. A valley fill occupying so large a portion of the landform seems to be exaggerated. Therefore, the Atlas Member may be subdivided into two parts, with the lower unit belonging to the valley fill and the upper unit being possibly deposited in a broad floodplain environment without prominent topographic relief.

Isopach Map of the Cantuar Formation (Figure 10)

The isopach map of the Cantuar Formation displays the similar distribution style to the Dimmock Creek Member, which may indicate that the latter constitutes the major body of the valley fill. This is the reason that the Dimmock Creek Member is chosen as the identification criterion of Cantuar valley during well log correlation. The thickness is up to 60 metres, which may indicate the maximum depth of the valley incision in the study area.

CONCLUSIONS

The Cantuar Formation and the adjacent strata in southwestern Saskatchewan demonstrate characteristic log responses, which can be identified and correlated by integrating the three major approaches (marker beds, unit association correlation, and consideration of depositional environment). The valley fill and interfluvial deposits form two readily distinguished log patterns.

Ten cross sections constitute the control grid of interwell correlation and present the greatly variable paleomorphology across the study area during the deposition of the Mannville Group. Four isopach maps reflect the progressive valley fill from the thalweg (base), through the terrace, to the edge (top) of the valley, and the general valley geometry.

Well log studies are of significant use in subsurface mapping and stratigraphic interpretation. However, they can only provide a general stratigraphic framework and interpretation of the depositional environments. More detailed and reliable results can be achieved on the basis of core-log integration, which will be conducted in the coming months.

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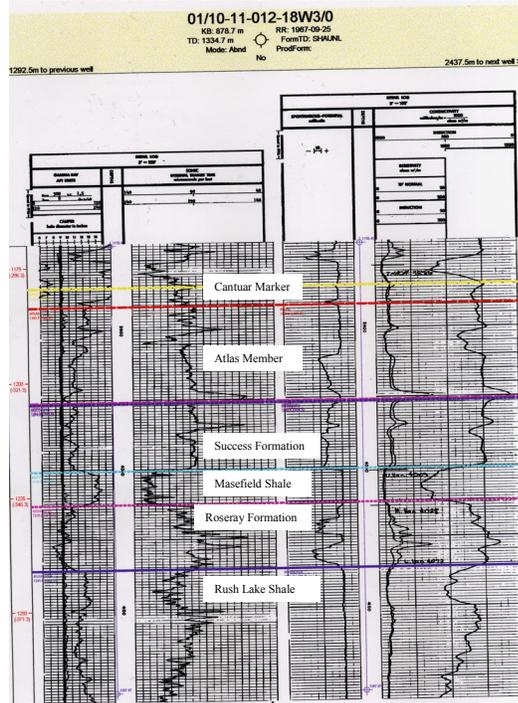
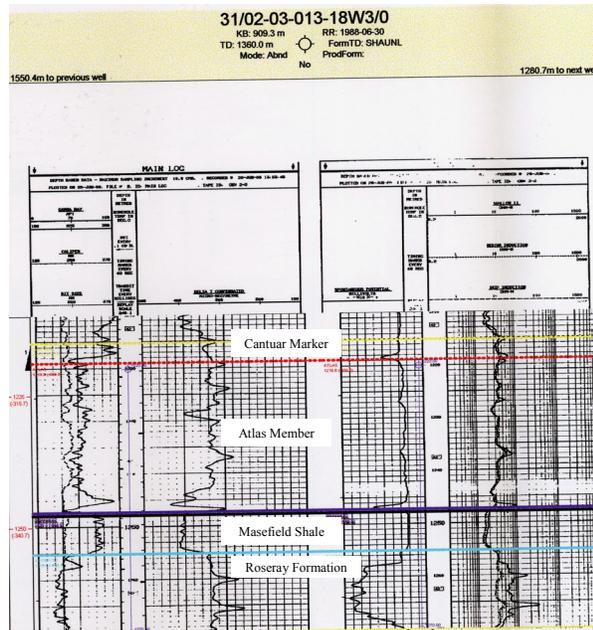
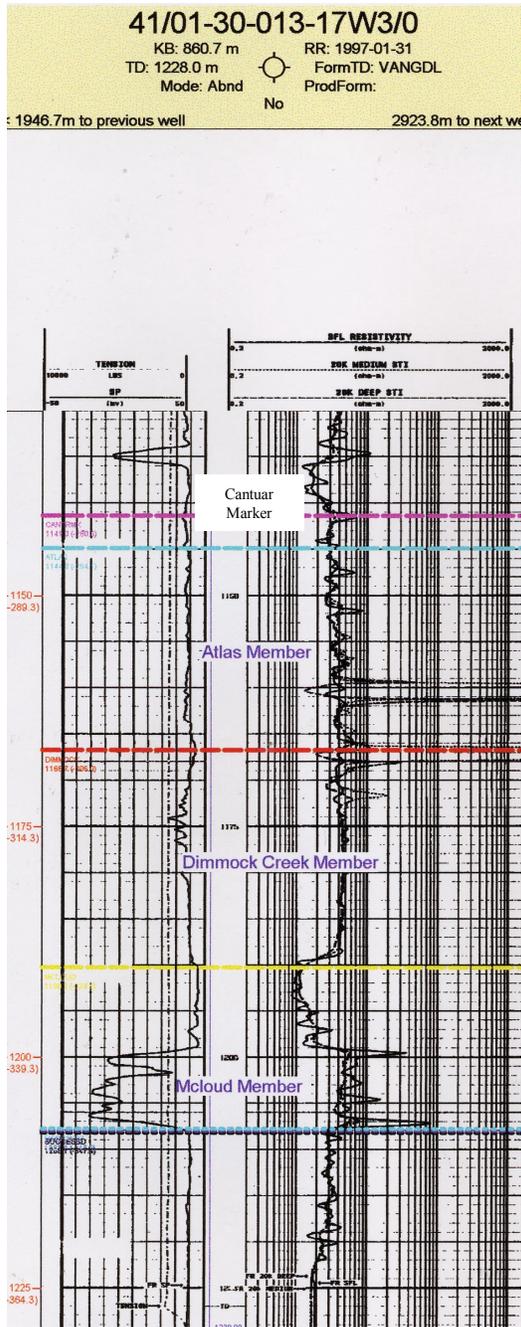


FIG. 5. Typical log characters of the studied formations or members.

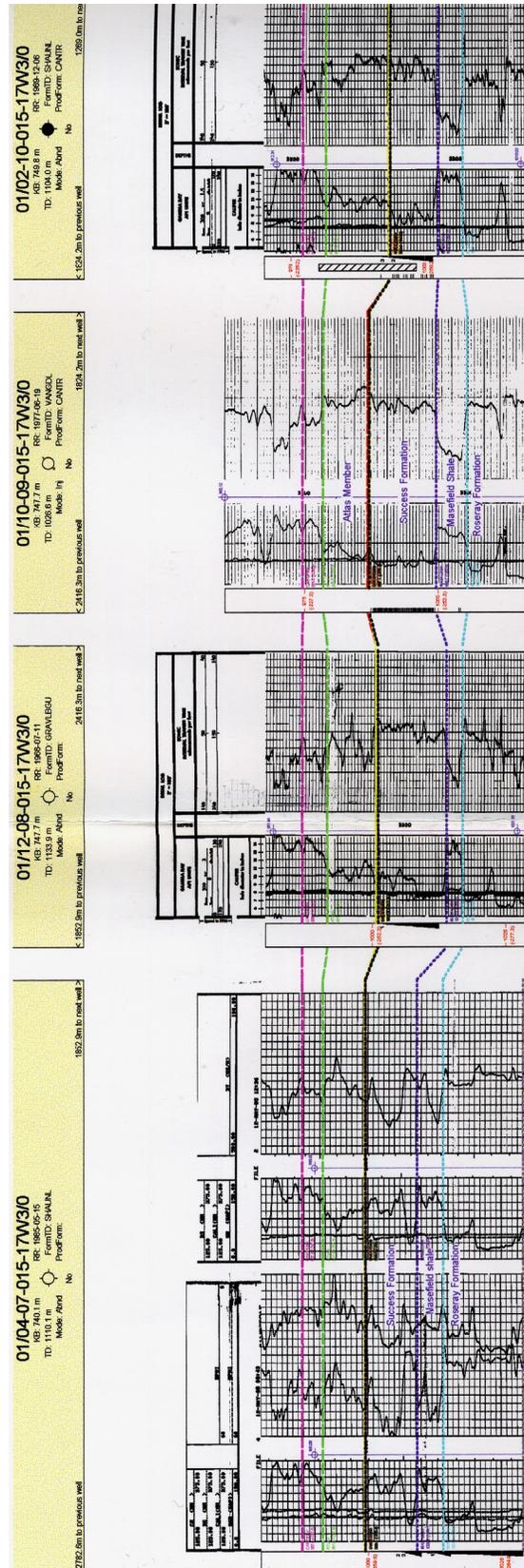
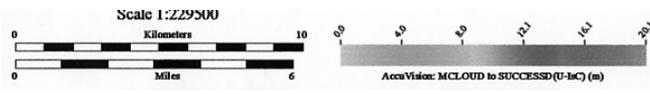
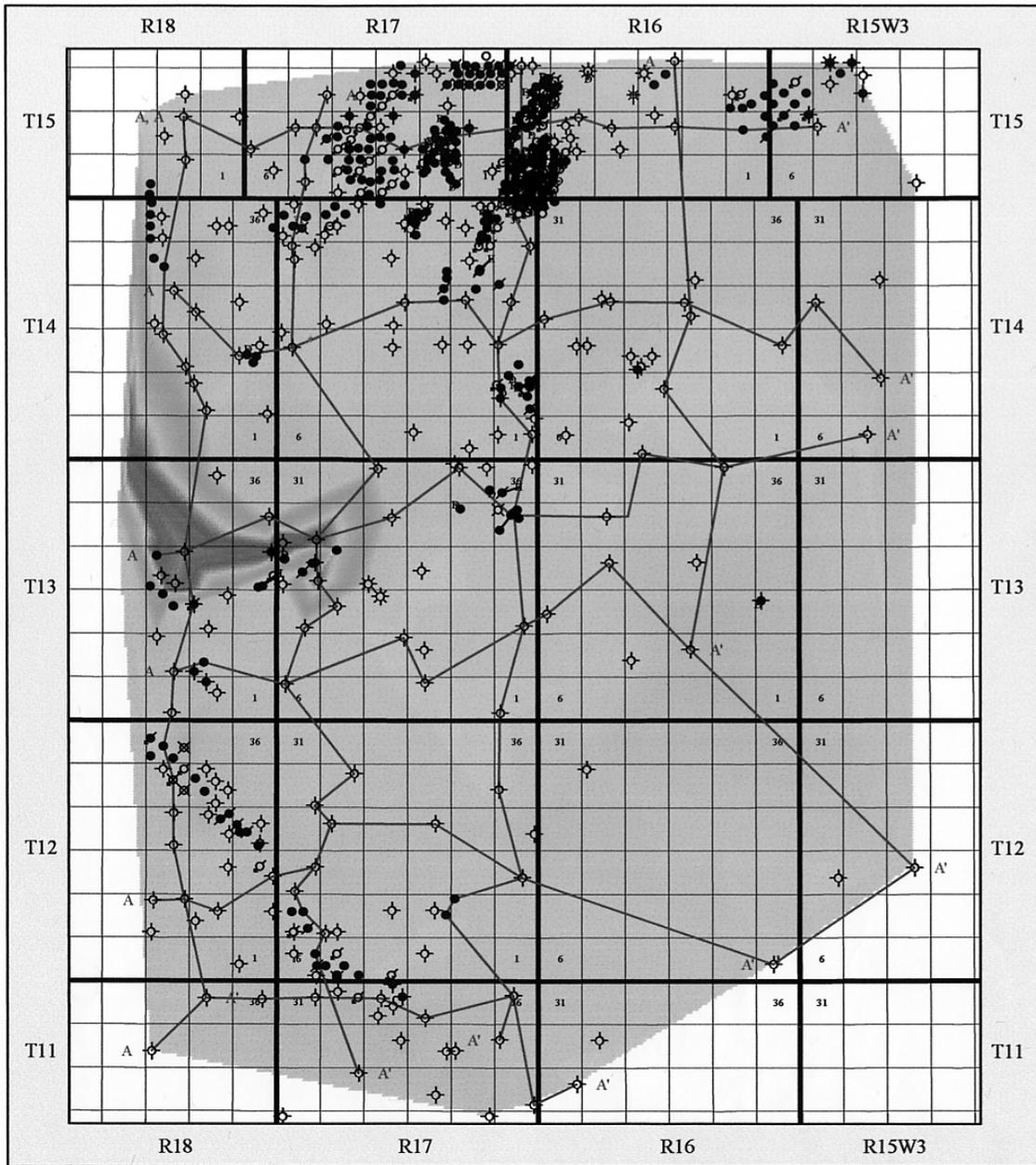


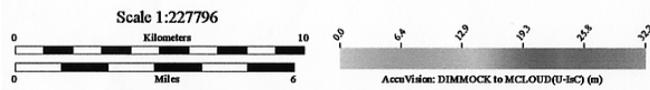
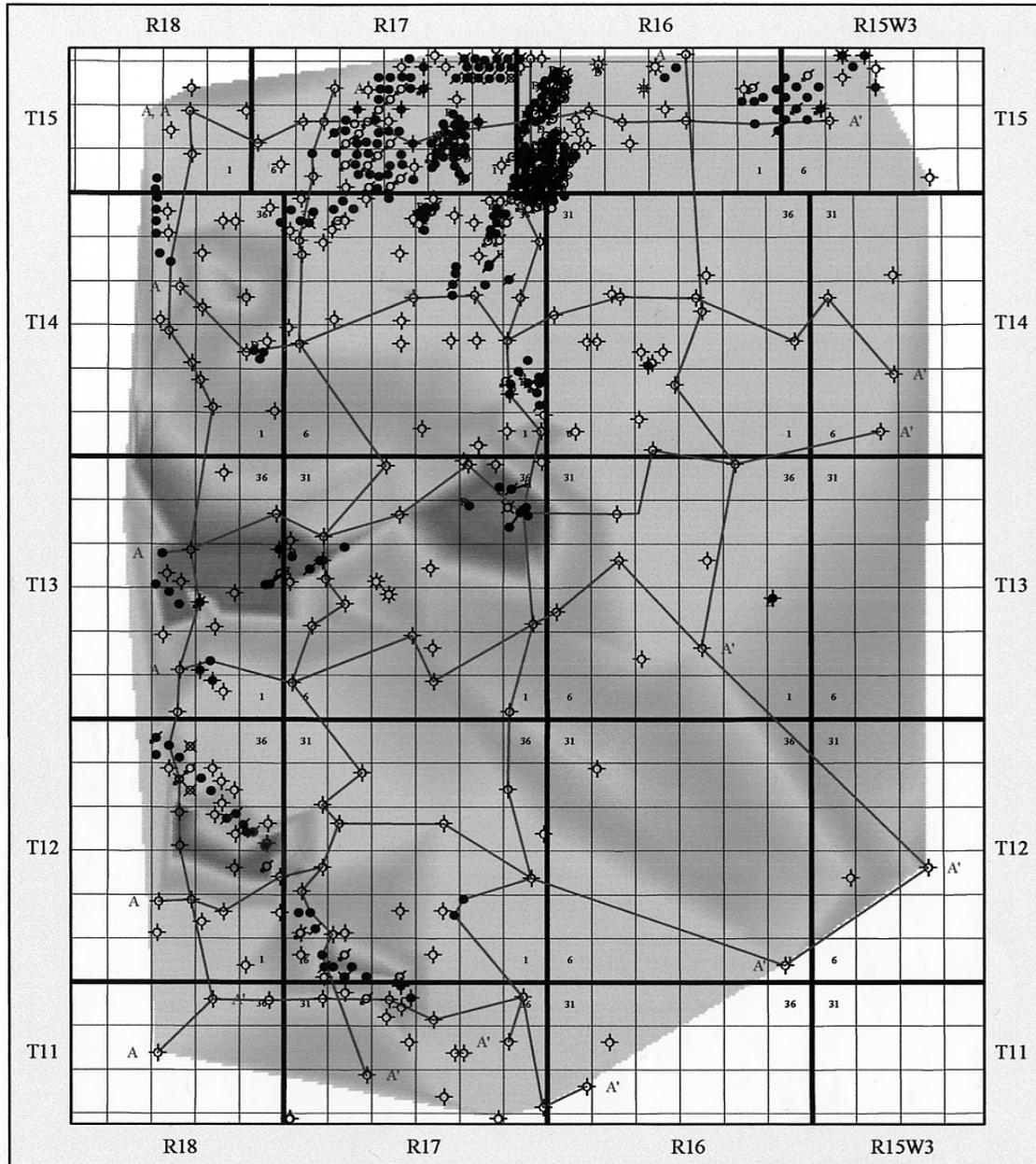
FIG. 6. Part of cross section W-E-1.



WELL LEGEND	
Bottom Hole Locations:	
○ Location	⌘ Service or Drain
● Oil	⊛ Gas
◇ Dry & Abandoned	⊞ Suspended Oil
⊕ Abandoned Oil	⊛ Abandoned Gas
⊗ Abandoned Service	⊞ Injection
Surface Hole Locations:	
—○— Directional	—□— Horizontal

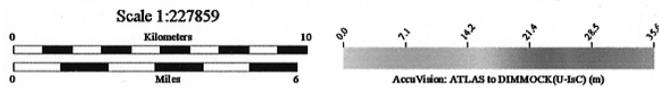
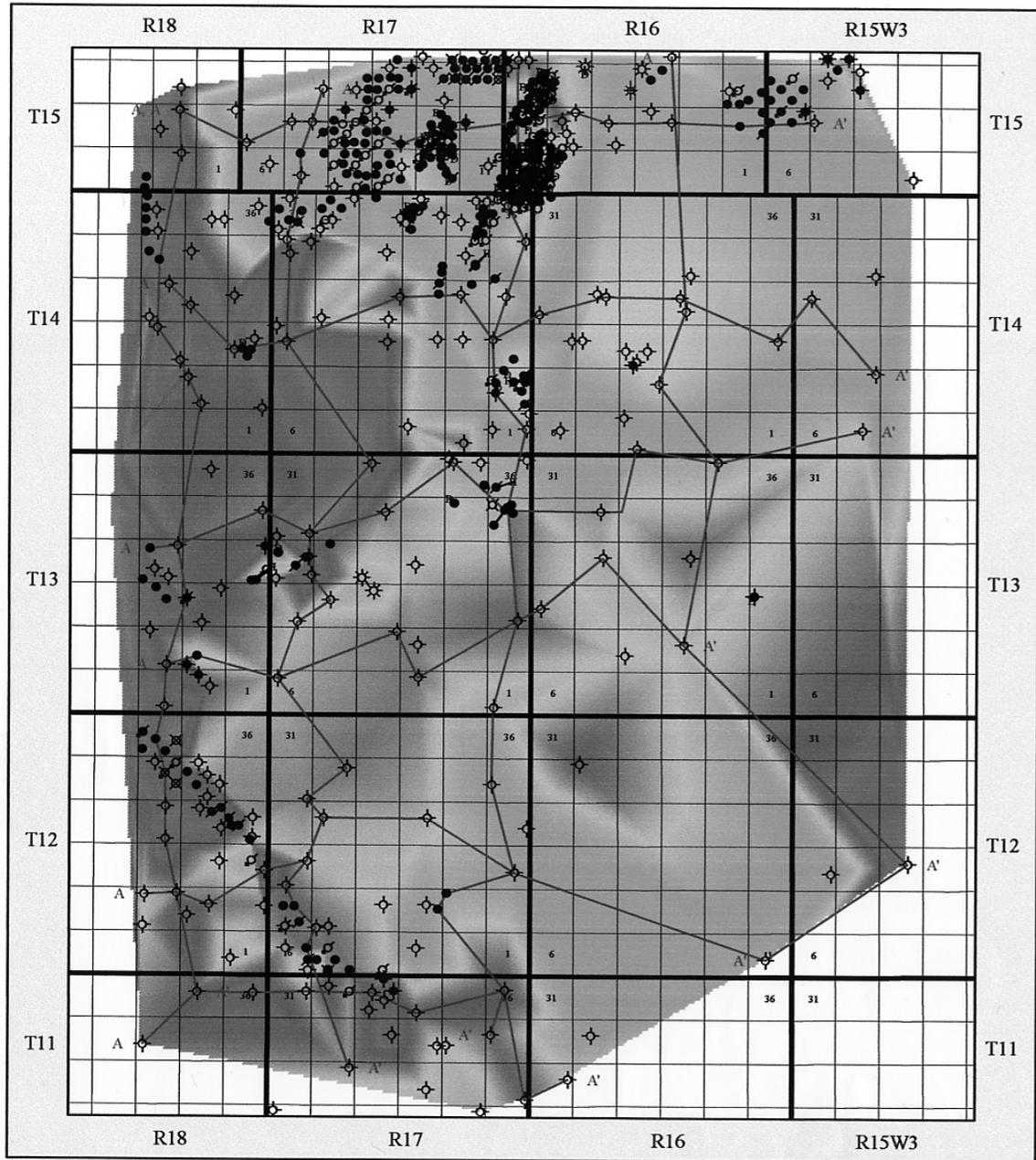
WELL LISTS	
⊛	vertical wells
⊛	cantr prod

FIG. 7. Isopach map of the McCloud Member.



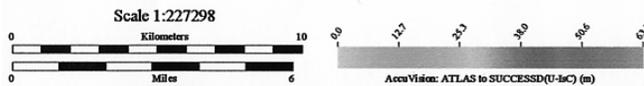
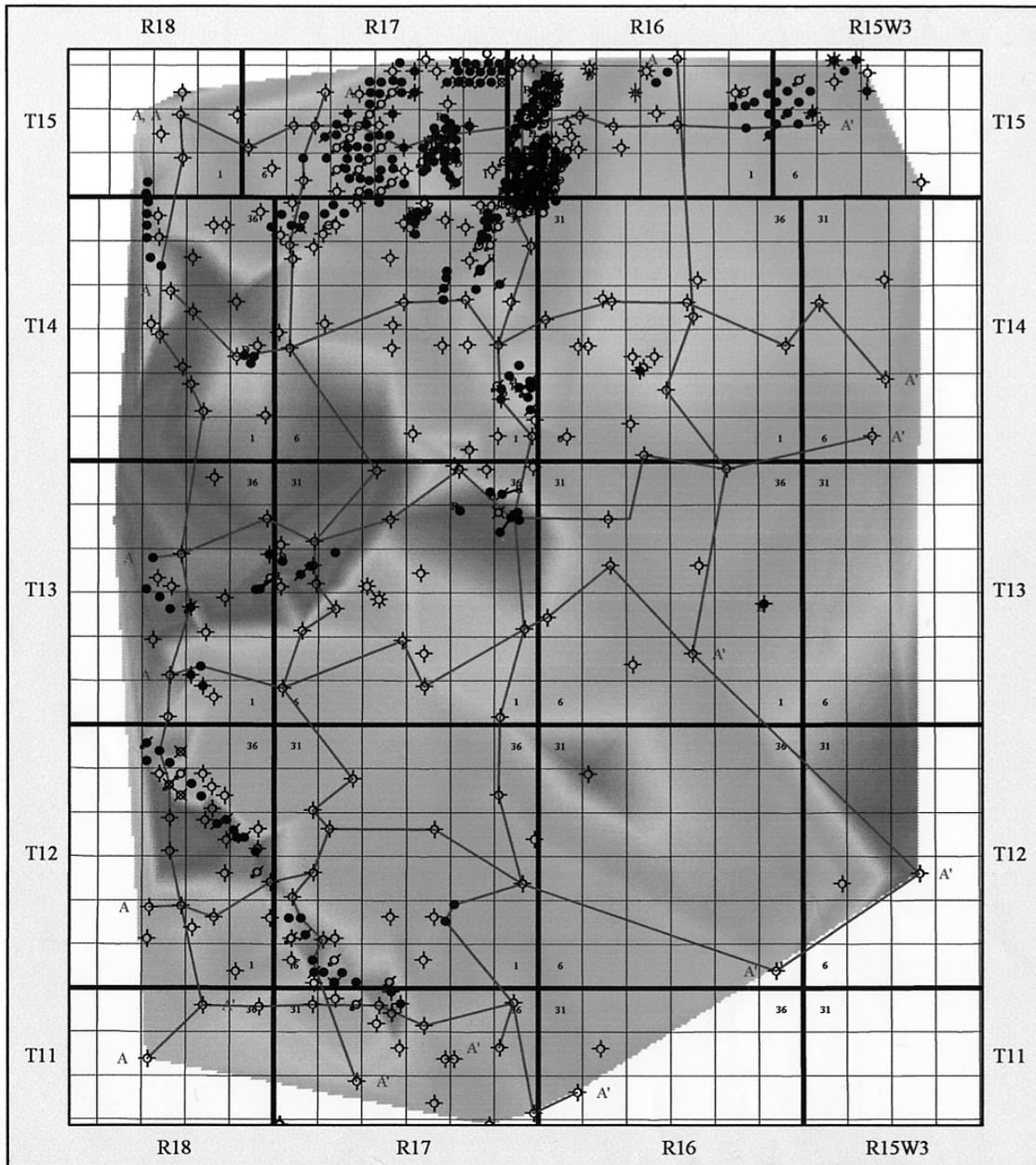
WELL LEGEND	
Bottom Hole Locations:	
○ Location	⌘ Service or Drain
● Oil	✱ Gas
◇ Dry & Abandoned	⌘ Suspended Oil
✱ Abandoned Oil	✱ Abandoned Gas
⌘ Abandoned Service	⌘ Injection
Surface Hole Locations:	
○ Directional	— Horizontal
WELL LISTS	
✱	vertical wells
✱	cantr prod

FIG. 8. Isopach map of the Dimmock Creek Member.



WELL LEGEND	
Bottom Hole Locations:	
○ Location	⌘ Service or Drain
● Oil	⊗ Gas
◇ Dry & Abandoned	⊠ Suspended Oil
⊕ Abandoned Oil	⊗ Abandoned Gas
⊗ Abandoned Service	⊠ Injection
Surface Hole Locations:	
○ Directional	— Horizontal
WELL LISTS	
⊗ vertical wells	
⊗ cantr prod	

FIG. 9. Isopach map of the Atlas Member.



WELL LEGEND	
Bottom Hole Locations:	
○ Location	⊠ Service or Drain
● Oil	⊠ Gas
◇ Dry & Abandoned	⊠ Suspended Oil
⊠ Abandoned Oil	⊠ Abandoned Gas
⊠ Abandoned Service	⊠ Injection
Surface Hole Locations:	
—○ Directional	—⊠ Horizontal
WELL LISTS	
⊠ vertical wells	
⊠ cantr prod	

FIG. 10. Isopach map of the Cantuar Formation.