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Challenges from North to South
Des défis du Nord au Sud

Steepbank River Valley Geomorphological and Geological Categorization

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ABSTRACT
Natural terrain hazard assessments require the development of geomorphological and engineering geological maps to understand the past and current performance of the natural river valley slopes. This paper outlines the approach adopted for the geomorphological and engineering geological inventory maps developed for the natural riverbank slopes along the Steepbank River Valley escarpment in Fort McMurray, Alberta.

The inventory maps document the location and spatial distribution of the observed major slope movements and geological features as well as the current physical conditions of the River Valley escarpment slopes. These maps provide an understanding of the nature and magnitude of the various potential hazards in the natural slopes and are considered to be representative of baseline conditions against which future conditions can be compared. The available aerial photographs and LiDAR-derived topographic contours indicate that on-going regression of the escarpment slopes is occurring as a result of natural processes.

RÉSUMÉ
Les évaluations du risque de terrain naturel requièrent l'élaboration des cartes géomorphologiques, ainsi que celles de génie géologique afin de comprendre les performances passées et actuelles des pentes naturelles d'une vallée fluviale. Cet article décrit l'approche adoptée pour les cartes d'inventaire géomorphologiques et celles de génie géologique développées pour les pentes naturelles des berges le long de l'escarpement de la vallée de la rivière Steepbank située à Fort McMurray, en Alberta.
Les cartes d'inventaire documentent la localisation et la distribution spatiale de majeures instabilités observées, les caractéristiques géologiques, et les conditions physiques actuelles des pentes de l'escarpement de la vallée fluviale. Ces cartes fournissent une compréhension du type et de l'amplitude de divers risques potentiels d'instabilité pour les talus naturels et elles sont considérées comme représentatives des conditions de base par rapport auxquelles les conditions futures peuvent être comparées. Les photographies aériennes et les données d'arpentage disponibles indiquent qu'une régression continue des pentes de l'escarpement se produit à la suite des processus naturels.

1 INTRODUCTION

Geomorphological mapping is a key tool used to understand the evolution of the landscape and the potential hazards associated with its present day form. Geomorphological and engineering geological maps are complementary to each other and natural terrain hazard assessments require a combination of both approaches in order to assess the nature, magnitude and frequency of the various hazard types (Parry et. al., 2006). Integration of the two approaches combines the short-term static with the longer dynamism of the landscape with respect to natural terrain hazards (Hearn, 2002).

The Steepbank River Valley escarpment study area is located 90 km north of Fort McMurray, Alberta within Township 92 and Range 9W4 (Figure 1). The study area is approximately 5.7 km long along the escarpment natural slope on the north side of the Steepbank River. This paper presents the approach adopted for the geomorphological and engineering geological inventory maps developed for the natural riverbank slopes along a segment of the Steepbank River Valley escarpment.

Figure 1. Overview of the greater Fort McMurray area and location of the study area along the Steepbank River.

2 LOCAL GEOLOGY

The stratigraphy along the escarpment slope study area was interpreted based on a review of available geotechnical and geology borehole information in the area.

In general, the subsurface stratigraphy consists of a thin layer of Holocene muskeg, underlain by Pleistocene deposits, Cretaceous Clearwater and McMurray Formations, and the Devonian Waterways Formation.

The Holocene deposit typically consists of a thin layer of muskeg.

The Pleistocene deposits underlying the muskeg typically consist of glacio-lucustrine/glacio-fluvial sands or silts overlying glacial tills (sandy, silty and/or clayey tills). The Pleistocene deposits have a variable thickness generally ranging from 0 m to 20 m and are generally more clayey towards the northwest.

The Cretaceous Clearwater Formation, which underlies the Pleistocene deposits unconformably, consists of silty clay to clay shale of high plasticity and is typically pre-sheared. The available borehole data suggests that the Clearwater Formation ranges between 7 m and 32 m in thickness with the thicker Clearwater Formation present towards the southeast.

The Cretaceous McMurray Formation generally consists of fine-grained bitumen saturated sands with variable interbeds of clayey and fine-grained facies. The thickness of the Formation varies approximately from 47 m to 84 m.

The Devonian Waterways Formation unconformably underlies the McMurray Formation. The surface of the Devonian Waterways Formation can be highly variable. This is likely a result of salt dissolution of the underlying Middle Devonian Prairie Evaporite Formation which leads to collapse of the overlying Upper Devonian Waterways Formation.

The Waterways Formation consists of limestones and calcareous shales. The top of this formation is frequently capped with a clay rich Paleosol unit that is present throughout much of the study area. This unit was typically described as slickensided in the available borehole records.

3 TOPOGRAPHY AND LANDFORM CHARACTERISTICS

The ground surface topography above the River Valley escarpment slopes gradually downward toward the west. The Steepbank River flows from east to west. The natural slope height ranges from approximately 60 m to 70 m throughout the study.

The River Valley escarpment natural slopes can be generally divided into uplands, escarpment slopes and Steepbank River bank. The slope crest of the River Valley escarpment is defined as the transition point between the flat upland slope (generally shallower than 20H:1V) and the relatively steep upper slope (generally between 3H:1V and 10H:1V). The uplands and the escarpment upper slopes are generally densely vegetated and mostly undisturbed. The escarpment slopes are covered with colluvium of a silty and sandy composition, and occasionally bituminous sand. Talus slopes are present in some areas near the toe of the escarpment slopes, which are likely due to crest loss, sloughing and/or historic slope failures. Fallen trees and inclined trees are evident in some areas, which can be indicative of slope movements. The river banks are constituted by recently deposited alluvium in contact with the Lower McMurray Formation.

The geomorphology along the escarpment slopes was reviewed by calculating the overall surface gradient of the natural slopes using recent LiDAR-derived contours. The slope geometry and surface gradient vary significantly over the study area. Figures 2 and 3 provide a general overview of two typical types of slope profiles.

Figure 2 represents a typical profile of the escarpment slopes within the study area and the surface gradient is summarized as follows:

- The uplands are generally shallower than 20H:1V and are likely composed of Holocene Muskeg and Pleistocene glacial overburden;
- The upper slope of the escarpment is generally between 3H:1V and 6H:1V and is likely composed of glacial overburden and the Clearwater Formation;
- The lower slope of the escarpment is generally close to or steeper than 1.5H:1V, and can be as steep as 0.7H:1V in some localized areas and is mainly composed of the McMurray Formation; and
- The river bank is generally shallower than 30H:1V and is likely composed of Holocene colluvium and/or fluvial material.

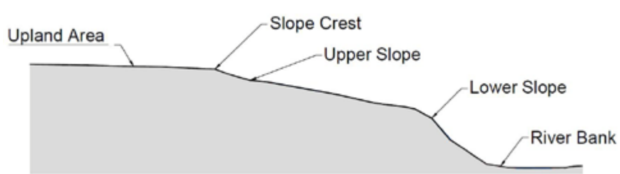


Figure 2. A typical profile of the Steepbank River Valley escarpment slopes.

Figure 3 is a section through a historical large-scale landslide area as shown in Figure 4. The overall slopes with large-scale slope failures in the study area range typically from 3.5H:1V to 6.5H:1V.

Figure 3. A section through a historical large-scale landslide area in Figure 4.

4 GEOMORPHOLOGICAL CHARACTERIZATION

4.1 Observations on Historic Aerial Photos

There are 85 historic aerial photographs (stereo pairs) from 1950, 1967, 1972, 1974, 1976, 1981, 1984, 1997, 1998, 2001 and 2008 with scales varying from 1:15,000, 1:20,000, 1:21,120, 1:40,000, 1:50,000, 1:60,000 and a few sets without the scale identified. The information obtained from the aerial photo interpretation is limited to a general overview, due to the generally large scales of the aerial photos relative to the size of the study area, making it difficult to clearly identify tones, structures and patterns displayed on the aerial photos. The flight lines (directions) and aerial photos numbers (coverage) also limited the observations.

Small-scale slope instability features such as sloughing, fallen/inclined trees and crest retrogression are difficult to, or cannot be identified in photos with scales of 1:15,000 or greater. Vegetation is difficult to identify on photos with scales of 1:40,000 or greater. Erosional gullies and large-scale failures are difficult to identify (depending on the size of the feature) on scales of 1:50,000 or greater. Seepage could not be identified on any scale of the aerial photos available.

Observations were conducted on the stereo-pair historical aerial photographs and key slope instability features that could be visually identified were mapped, such as large-scale historic failures, apparent erosional gullies and apparent sloughing near slope toe.

4.2 Observations on Recent Photos

Recent photos taken in 2007, 2009, 2010, 2012, 2013 and 2014 were reviewed to visually identify slope instability and seepage related features in the geomorphological process. These photos were taken either by foot/boat traverses along the river valley or during helicopter tours. Slope instability and hydrogeological key features identified were grouped into four types, including:

- active, retrogressive features in a relatively small-scale, such as slope crest retrogression, talus slopes near slope toe, surficial sloughing, and fallen/inclined trees;
- erosional gullies;
- large-scale historic failures; and
- hydrogeological features including signs of seepage and bitumen seeping.

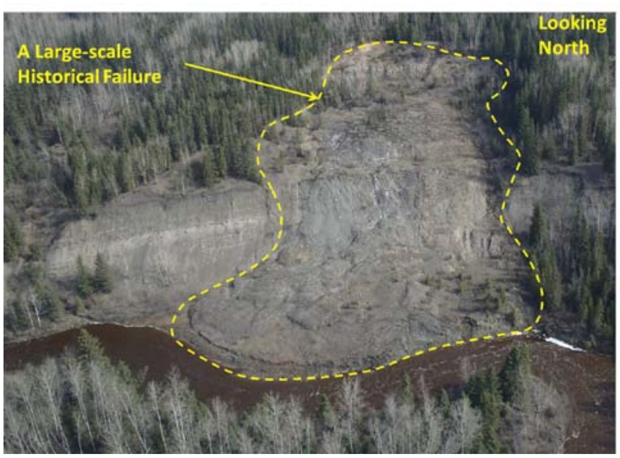


Figure 4. An example of a large-scale historical failure observed along the escarpment slopes.

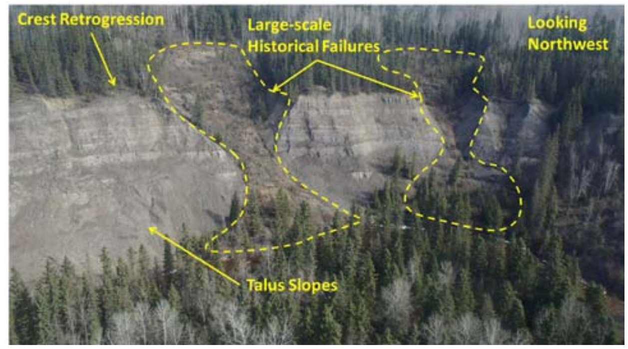


Figure 5. An example of large and small-scale failures along the escarpment slopes.

Key features visually identified on these photos include large-scale slope movement features such as erosional gullies and large-scale historical failures (Figures 4 and 5). Small-scale or detailed features such as crest retrogression, sloughing, fallen/inclined trees, fractured bedrock, signs of seepage, bitumen seeping and salt precipitate, etc. were identified in areas where photos are available (Figures 6 and 7). In a few areas the slope toe undermined by the river likely during storm/high flow events causing lateral erosion was also observed.

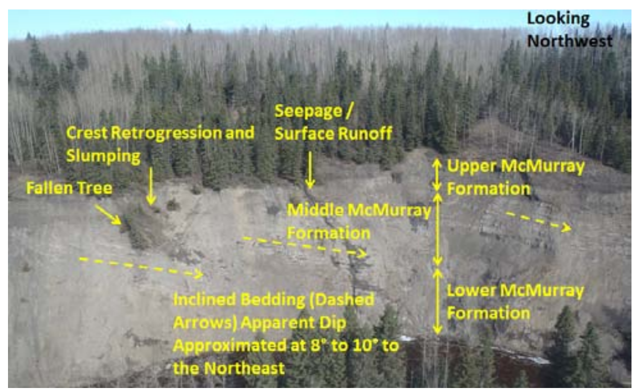


Figure 6. An example of several key features observed along the escarpment slopes.

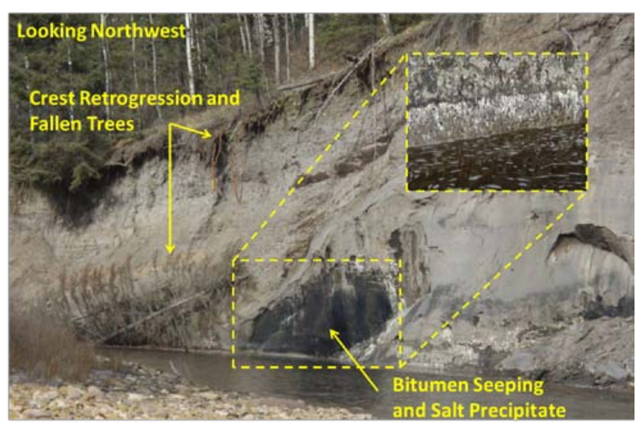


Figure 7. An example of small-scale failures and bitumen seeps along the escarpment slopes.

4.3 Geomorphological Categorization

4.3.1 Spatial Distribution

Key features identified in the study area were mapped with polygons and symbols on the LiDAR-derived topographic contours, based on surface tone and texture, vegetation, feature type, approximate location and size, and likely material type that could be visually identified on the available photographs. It should be noted that mapping of the key features is limited by a range of factors, such as availability and scales of the photographs, the coverage of photographs and the ground cover (e.g. snow and leaves). As such, it is possible that not all slope movement and hydrogeological features, including signs of seepage and bituminous seeps, have been captured in the study area.

Inventory maps were developed, showing the location and spatial distribution of the above observed features as of 2012. Figure 8 shows a portion of the inventory map developed along the escarpment natural slopes.

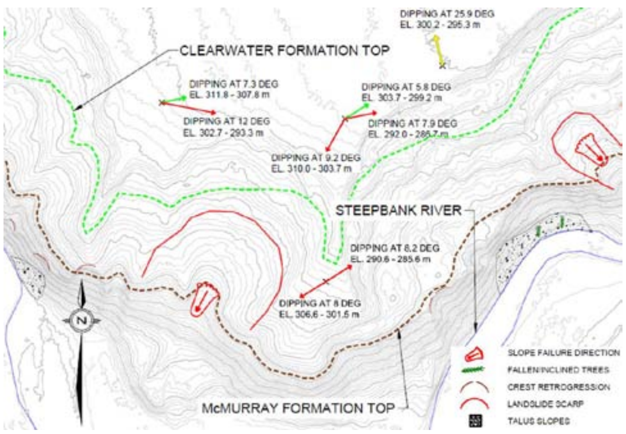
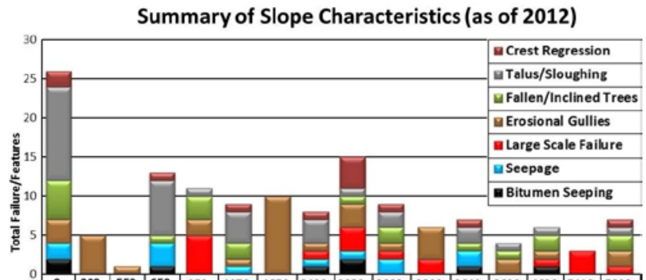


Figure 8. A portion of the inventory map along the escarpment slopes with slope movement features mapped.

4.3.2 Density Distribution

To track the numbers of the geomorphological and hydrogeological key features along the escarpment slopes, the density distributions of the observed features along the escarpment slope as of 2012 are plotted in Figures 9 and 10 respectively.

The dominant types of observed slope instability features are active, relatively small-scale retrogressive features such as crest retrogression, sloughing, and fallen/inclined trees. These types of features make up approximately 48% of the features mapped. Approximately 80% of these features took place on areas where steep slopes are present. The sloughed materials form talus slopes near the river bank appear to be composed predominately of Clearwater Formation and/or McMurray Formation.



	0-200	200-550	550-650	650-850	850-1370	1370-1550	1550-2100	2100-2350	2350-2900	2900-3300	3300-3640	3640-3960	3690-4630	4630-5110	5110-5380	5380-5770
Crest Regression	2	N/E	X	1	X	1	N/E	1	4	1	N/E	1	X	X	X	1
Talus/Sloughing	12	N/E	X	7	1	4	N/E	3	1	2	N/E	2	1	1	X	1
Fallen/Inclined Trees	5	N/E	X	1	3	2	N/E	X	1	2	N/E	1	1	2	X	2
Erosional Gullies	3	5	1	X	2	1	10	1	3	1	4	X	2	1	X	2
Large Scale Failure	X	X	X	X	5	X	X	1	3	1	2	X	X	1	3	1
Seepage	2	N/E	X	3	N/E	1	N/E	1	1	2	N/E	2	X	X	N/E	X
Bitumen Seeping	2	N/E	X	1	N/E	X	N/E	1	2	X	N/E	1	X	1	N/E	X

Figure 9. Numbers of key features observed along the escarpment slopes as of 2012 (Notes: Chainage starting from West towards East; Number – total of each key feature observed; X – key features non-existent; N/E – key feature not evident on information available due to material (e.g. snow) cover, photo directions and/or scale).

Erosional gullies are the second most observed slope features. Erosional gullies likely developed by increased surface run-off over long periods of time. The erosional gullies observed within the study area range from a few meters long to extending from the upland down to the river bank. This type of feature makes up approximately 26% of the slope features mapped.

Large-scale (retrogressive) historical slope failures have been identified at eighteen locations. This type of failure makes up approximately 12% of the slope features mapped. Approximately fifteen historical large-scale slope failures are considered ancient (over 75 years old). Three historical large-scale slope failures are likely recent (two failures likely occurred in the 1940's and the other one likely occurred between 1975 and 1980).

Hydrogeological features, including signs of seepage and bitumen seeping, make up approximately 14% of the features mapped.

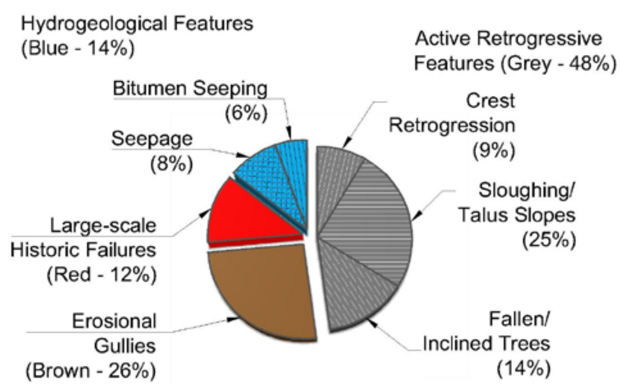


Figure 10. Density distributions of existing slope movement and hydrogeological features as of 2012.

4.3.3 Activity Distribution

Relatively continuous photo records in the last a few years were available near the west segment of the study area. Based on the observations in this area, it appears that:

- Talus slopes/sloughing was observed at the same locations in 2007, 2009, 2010 and 2012 with slightly increased accumulation between the above noted years;
- Fallen/inclined trees were observed in 2007, 2009, 2010 and 2012 with newly fallen trees observed in the photos in 2007 and 2012;
- Crest retrogression was observed at the same locations in 2007, 2009, 2010 and 2012 with no significant changes in the photos between the above noted years;
- Erosional gullies showed no significant change in this period but were observed on photos in 2007, 2009, 2010 and 2012; and
- New large-scale failures were not observed in the last 7 year period.

Observations of seepage and bitumen seeping are incomparable due to the scales and direction of the photos and the ground cover (e.g. snow and leaves). These features were not captured on the photographs taken after 2007, although they may exist. Thus the occurrence of their frequency is inconclusive.

Photographs near the west segment of the study area in the last seven years show active, retrogressive small-scale slope failures on the riverbank slopes. It is likely that the small-scale slope movement will continue to be active in the future, although continuing retrogression of the crest appears to be relatively minor on an annual basis each year.

Figure 11. A bent tree near the west segment of the study area suggesting slow slope movement.

5 GEOLOGICAL CHARACTERIZATION

To gain an understanding of the geologic structural features along the escarpment area, geologic structural data was reviewed in the study area. The data reviewed includes available geotechnical and geology resource borehole records, geophysical logs, core photos and core descriptions.

5.1 Dipping Trends

Dipping beds within the Cretaceous Clearwater and McMurray Formations are presumed to be preserved sedimentary structures that occurred during sedimentation. Little or no post-depositional deformation (i.e. tectonism) was assumed in the study area in the sedimentary package above the Precambrian shield. Fluvial, tidal, and marine influenced depositional environments are known to produce dipping beds. These environments are common in the McMurray Formation and to a lesser extent in the Clearwater Formation where a deeper marine depositional environment prevailed. It is possible that dipping beds in the project area may be caused by collapse structures and/or glaciotectonism. Dipping beds formed in this nature would likely have considerably higher dip angles than those deposited as sedimentary structures.

Dipmeter data can be utilized to identify dipping trends and to determine the dip angle and dip direction for geologic structures. The dipmeter is essentially a multi-arm micro-resistivity log. Deviations (kicks) on the logs are correlated and the amount and direction of bedding dip can be calculated. It should be noted that bedding is most frequently responsible for resistivity shifts for surveys conducted in sedimentary sequences. However, joints, faults and fractures may also be represented. Dipmeter data alone cannot differentiate between these types of structures. For this review it was assumed that the dipmeter data from the geophysical logs represents bedding only.

To identify potential unfavourably dipping geologic structures for the River Valley escarpment slopes, a screening criterion was incorporated by examining the tadpole plots to define a potential dipping trend (Figure 12), including dip direction/azimuth, dip angle, thickness (consistently concentrated dip directions occur with significant thickness) and geologic units.

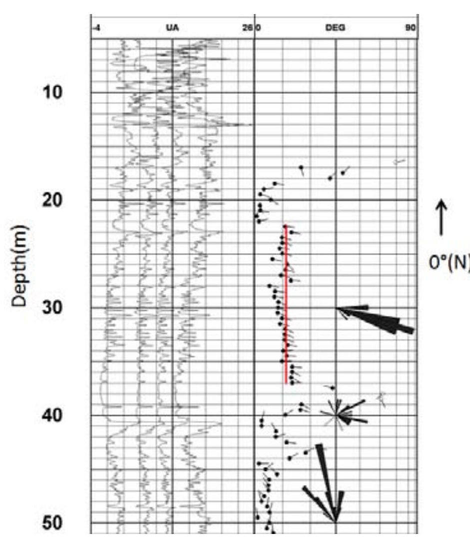


Figure 12. A typical dipping trend (red line) identified in the dipmeter data (dipping trend from 22.5 m to 37.0 m dipping at 10.4° and dip direction of 102° in tidally influenced sand and mud of the McMurray Formation).

Dipmeter data review was conducted to identify unfavourable dipping clay beds. When the azimuth of the geological discontinuity is within ±20° of the strike of the slope face, or if the azimuth of the line of intersection by two or more geological discontinuities is within ±45° of the azimuth of the slope face (Hoek and Bray, 1981), the strike is considered unfavourable. In cases where two trends are intersecting, the minimum and maximum strikes have been selected from the two strike values to reflect the River Valley escarpment. It is understood that in the presence of continuous release structures that strike near-perpendicular to the slope, toppling can occur at higher angles. These require friction angles less than the angle of dip of line of intersection. Dip angles daylighting in the slope face are considered unfavourable to the River Valley escarpment.

Dipping trends were frequently identified throughout the study area and are largely confined to the McMurray Formation. The majority of the dipping trends were observed to have a northerly component with dip azimuths that are favorable to the River Valley escarpment. There are exceptions where localized unfavorable (to the River Valley) dipping trends were identified (Figures 6 and 8). Unfavourable dipping trends may also exist in areas where borehole data is not available.

5.2 Faults, Joints and Folds

Structural deformation of bedrock units can occur during advancing and/or retreating glaciations (ice sheets) and is referred to as glaciotectonism. Glaciotectonic deformation in the upper bedrock units may result in faulting, folding, shearing and glacial rafting (ice thrusting).

Several glaciations have occurred in the study area. Loading and unloading of significant thickness of glacial ice may have caused jointing in brittle units (i.e. Clearwater Formation) and slickensides in high plastic clay units.

Faults can be identified by features such as visible slickensides along fault surfaces, a fault gouge or fault breccia formed along fault surfaces, and sedimentary structures that are cut off or offset along fault surfaces.
Joints can be identified based on natural discrete breaks on a rock mass.

Subsurface folds may be difficult to observe with borehole data but can be identified by features such as small scale micro-folding (crenulations), distorted bedding, high-angle dipping trends and overturned strata.

Core photos, core descriptions and photos taken along the River Valley escarpment can be utilized to identify potential faults, joints and folds (Figure 13).

High-angle joints (dips greater than 40°) and small-scale faults were frequently observed in the Clearwater Formation. The orientations of the discontinuities cannot be determined from the core descriptions or core photos alone. High-angle joints and small-scale faults with random orientations may be observed from existing dipmeter data; however, the dipmeter data does not differentiate between dipping beds and other geologic structures (e.g. joints and small-scale faults). The randomly oriented discontinuities are likely widespread throughout the Clearwater Formation and may be caused by glaciations.

No discernable folds were observed in the Clearwater or McMurray Formations in the study area.

Figure 13. A typical joint observed in the core from the Clearwater Formation

5.3 Collapse Structures

Dissolution of the Middle Devonian Prairie Evaporite Formation resulted in collapse of the overlying Upper Devonian Waterways Formation. This process resulted in the genesis of a wide collapsed karst valley/trough within the greater Fort McMurray region. Un-collapsed voids remained within the collapsed karst valley/trough prior to deposition of the Cretaceous sediments. The remaining voids frequently failed with the increased loading during the deposition of overlying units. These features are referred to as collapse structures in this paper.

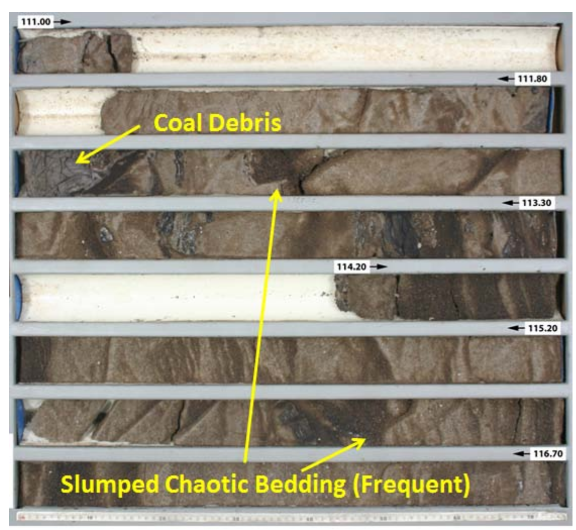


Figure 14. Typical chaotic and slumped bedding observed within the lower McMurray Formation overlying deeper Devonian limestone collapse breccias and paleosol infills (not shown).

Collapse structures were identified in the core photos (Figure 14) and core descriptions based on the following features:

- Slump structures in the collapsed sediments;
- Chaotic bedding in the collapsed sediments;
- Faults on and/or near the collapsed void;
- Joints above and/or near the collapsed sediments; and
- Dipping beds and coaly deposits in the resulting depressions.

Collapse structures can occur at various stages of deposition/geologic periods and the event is marked by the continued deposition of undeformed sediments. A collapse structure that has occurred during the Holocene Period may have a distinct circular surface profile. The LiDAR-derived topographic contours may be used in the future to identify late stage Holocene collapse structures.

Collapse structures were frequently observed in the Devonian units in the available core photos and core descriptions. The majority of the collapse structures occurred prior to the deposition of the McMurray Formation. These structures are marked by steeply dipping and erratic limestone bedding, limestone breccias and clay beds/Paleosol infills.

The collapse structures occurring during the deposition of the McMurray Formation often result in slump structures in the existing sediments. Slumped sediments can yield normal faults along with steeply dipping beds. These structures are marked by slumped McMurray sediments (erratic and steeply dipping beds), by limestone and McMurray Formation breccias and by clay (Paleosol) and McMurray Formation infills. Collapse structures within the McMurray Formation were observed in six boreholes, which are likely isolated occurrences (Figure 15).

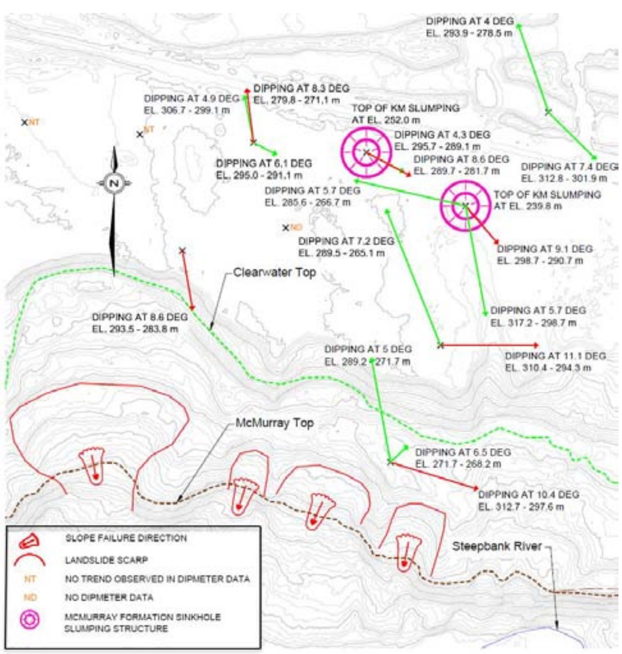


Figure 15. A portion of the inventory map along the escarpment slopes with collapse structures, dipping trends and slope movement features mapped.

The localized nature of the collapse structures indicates that they are relatively small in scale. These features may be present in between the available borehole locations where no borehole information is available for review.

5.4 Geological Structure Categorization

5.4.1 Spatial Distribution

The key geologic structural features identified in the study area are annotated on the LiDAR-derived topographic contours, together with historical and recent slope failures (if present) as of 2012 (Figures 8 and 15). It should be noted that mapping of these key features was limited by a range of factors such as availability and scales of the dipmeter data, core photos and core descriptions.

5.4.2 Density Distribution

Density distribution of the numbers of the observed geologic structural key features is plotted in Figure 16, which is independent of the numbers of the observed geomorphological and hydrogeological features.

The dominant geologic structural feature observed in the study area is the high-angle joints (dips greater than 40°) and small-scale faults in the Clearwater Formation. This type of feature accounts for approximately 50% of the features mapped due to its widespread occurrence in the Clearwater Formation throughout the study area.

Unfavourable dipping trends were the second most observed geologic structural feature in the study area. This type of feature accounts for approximately 47% of the features mapped.

Collapse structures account for approximately 3% of the features mapped.

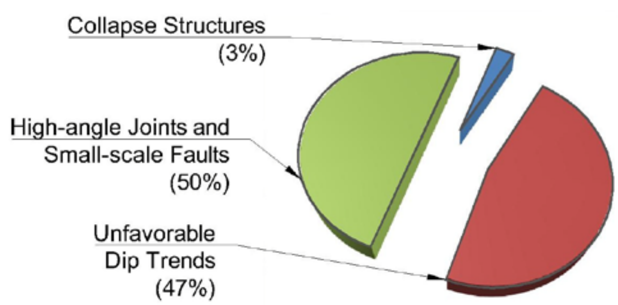


Figure 16. Density distributions of the geologic structural key features identified.

6 SUMMARY

Visual observations were made on available historical aerial photos, recent photos taken in 2007, 2009, 2010, 2012, 2013 and 2014, dipmeter data, core photos, core descriptions, and interpretation was made on LiDAR-derived contours of the Steepbank River Valley escarpment slopes. Inventory maps were developed, showing the location and spatial distribution of the dominant geomorphological, hydrogeological and geologic structural key features as of 2012.

The dominant geomorphological and hydrogeological key features in the study area include crest retrogression, talus slopes/sloughing, fallen/inclined trees, erosional gullies, large-scale historic failures, seepage, and bituminous seeps.

The dominant geologic structural feature observed in the study area is the high-angle joints (dips greater than 40°) and small-scale faults in the Clearwater Formation. Dipping clay beds and localized collapse structures with slumped McMurray Formation sediments were also identified.

The data contained in this paper is considered to be representative of baseline conditions in the River Valley study area. It should be noted that the key features mapped only document the current observed conditions of the natural riverbank slopes of the Steepbank River Valley escarpment as of 2012. These maps do not identify the susceptibility of slope movement or the probability of their occurrence or consequences in the future.

Signs of past slope failures indicate that the escarpment slopes in localized areas are marginally stable. It is prudent to suggest that the River Valley escarpment with existence of slope movement related features is considered susceptible to future occurrence of slope failures, regardless of how long ago the most recent slope movement occurred; and on-going regression of the escarpment slopes is occurring as a result of natural processes.

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