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THE COLUMBIA GLACIER, CANADA: A NEW VIEW

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ABSTRACT: *While nearly seventy percent of the world is covered by water, only 2.5 percent of it is fresh water. Most of the fresh water exists in glaciers and ice sheets in Antarctica and Greenland. Glaciers in these areas terminate mainly in oceans and do not provide much fresh water for human and environmental needs. Until recently ice created in alpine ice fields and distributed by their outlet glaciers has been a dependable source of fresh water but, a retreat of these glaciers has led to a decline in fresh water resources. Thus, it is essential to study and monitor these ice fields and glaciers with respect to fresh water availability. Most of these ice fields and glaciers exist in relatively inaccessible areas and little is known about them. Remotely sensed imagery offers an excellent means for inventorying and measuring changes in these glaciers. Until recently such imagery did not provide much information about these glaciers other than obtaining some basic measurements. This paper focuses on a new high resolution satellite image that covers the Columbia Glacier, an isolated outlet glacier linked to the Columbia Icefield in the Canadian Rockies.*

Keywords: *Columbia Glacier, Columbia Icefield, high resolution satellite imagery, remote sensing*

INTRODUCTION

Approximately 69 percent of the fresh water on the Earth's surface is contained in the frozen form of ice. More than 24 million km^3 (5.7 million cubic miles) of ice covers the Earth's surface (Gleick 1996). Most of this ice is concentrated in two places – Antarctica and Greenland. The remaining ice is spread across a few mountain ranges as alpine glaciers and ice fields. Ice that breaks away from Antarctica and Greenland flows directly into the oceans, converting it into salt water. The freshwater alpine glaciers feed many rivers that flow across the land providing water for human and environmental uses. It is these freshwater sources that need to be inventoried, monitored and protected. This paper centers on the Columbia Glacier, an alpine glacier, connected to the Columbia Icefield in the Canadian Rockies. More specifically, it introduces a new high resolution satellite image that provides both a synoptic and detailed view of the Columbia Glacier Basin. The paper looks at what types of information can be obtained from this high resolution satellite image with respect to inventorying and monitoring an alpine glacier and its basin. It is mainly a descriptive report, not an analytical study. The Canadian Rockies contain many alpine glaciers similar to the Columbia Glacier, with respect to remoteness and geomorphology; thus, an examination of this glacier might help in understanding other alpine glaciers, especially as it relates to their role as freshwater sources.

Straddling the boundary between the Canadian provinces of Alberta and British Columbia, the Columbia Icefield is the largest ice mass in North America, south of the Arctic Circle. Situated in the Canadian Rockies, this ice field covers an area of 337 km^2 (130 sq. mi.) and has a maximum depth of 366 m (1,200 ft.), the height of the Empire State Building in New York City. The average elevation of the ice field is about 3048 m (10,000 ft.). It occupies a high, flat-lying plateau and is called the Snow Done. The average snowfall across the ice field is 7 m (23 ft.) per year. Six large outlet glaciers flow from the Columbia Icefield, one being the Columbia Glacier. Water from these glaciers eventually drains into three different oceans namely the Atlantic, the Pacific and the Arctic. This triple divide is referred to as a hydrographic apex drainage pattern (Sanford 2010).

Figure 1 shows the Columbia Glacier in relationship to the Columbia Icefield. The glacier occupies the Upper Athabasca Valley and is the only outlet glacier on the northwest side of the Icefield. Also, it is the only glacier calving into a proglacial lake, which does not show on Figure 1. This unnamed lake forms the headwaters of the Athabasca River. The Athabasca travels 1,231 km (765 mi.) and its waters eventually enter the Mackenzie River system and into the Arctic Ocean. Figure 1 also shows Canadian Highway 93, known as Icefields Parkway. Four of the six outlet glaciers from the Columbia Icefield are within a short distance of the Parkway, and thereby, can be easily accessed. However, the Columbia Glacier is about 15 km (9.3 mi.) from the Parkway, going over the plateau's ice wall and ice field. It is a difficult route to traverse.

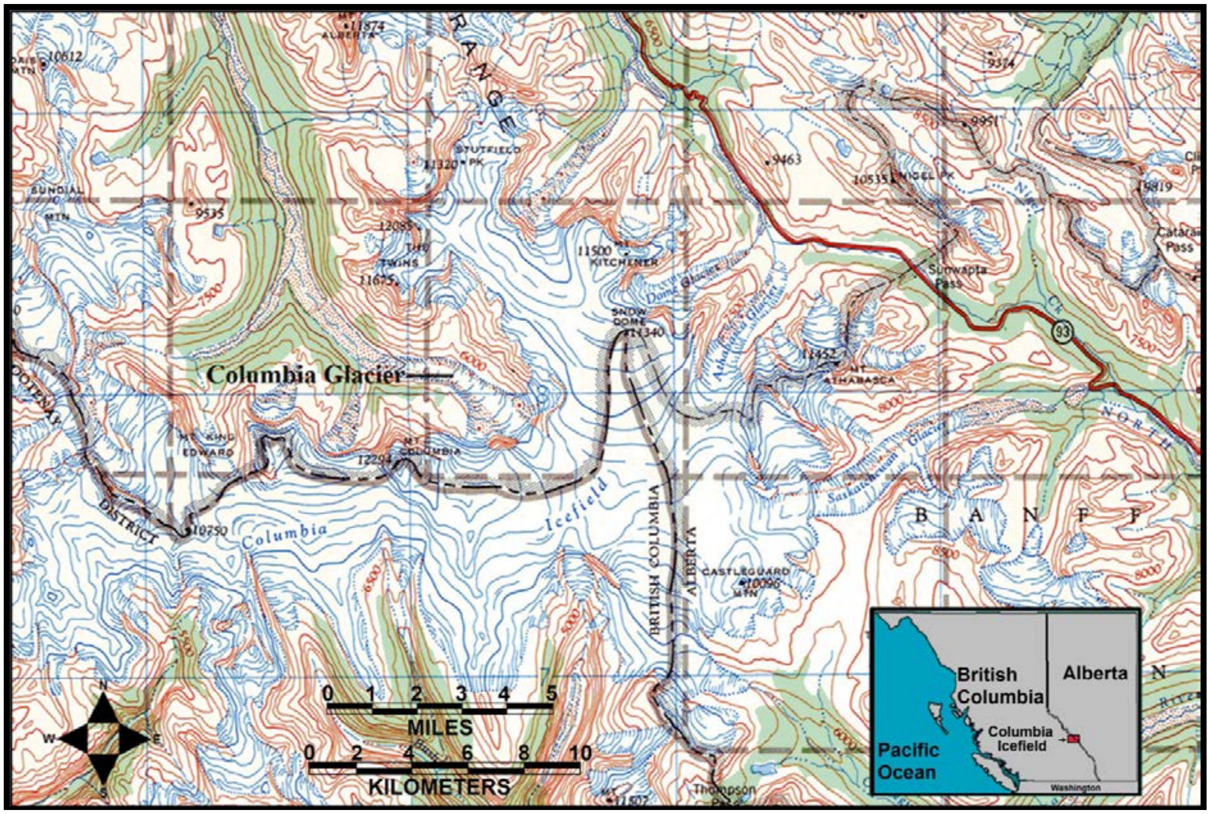

Figure 1: Columbia Icefield Topographic Map, 1960. Squares outlined by dashed lines cover 100 km^2 or 38.4 mi^2.

PREVIOUS INVESTIGATIONS

Like many alpine glaciers the Columbia Glacier, as previously indicated, is very isolated and difficult to reach. In the early 20th century only a few explorers and researchers ventured into the region and they found that they were limited to examining the terminus area (Habel 1902, Schaffer, 1908, Interprovincial Boundary Commission 1924, Palmer 1924, Howard Palmer 1924, 1925 and Field, 1949). Above the terminus the valley walls were very steep and had bare bedrock surfaces in many places, making it hard to hike the area in order to view the glacier's overall development. A 1924 high oblique aerial photograph taken as part of the Interprovincial Boundary Commission shows the entire glacier from a distance. The glacier at this date extended up to the terminus and no proglacial lake existed.

Later in the 20th century ground and aerial photography made it possible to record more about the Columbia Glacier Basin. The proglacial lake was first photographed in 1948 (Field 1949). Based on aerial photography the glacier in 1964 was 8.5 km (5.3 mi.) in length and expanded to 9.5 km (5.9 mi.) by 1980 (Pelto, 2017). Heusser(1954) found that the glacier had retreated 394 m (1293 ft) between 1724 and 1924. Baranowski and Henoch (1978) observed that the Columbia Glacier had advanced as much as 1 km from 1966 to1977. In a 1986 oral communication Parks Canada reported that the glacier had advanced farther completely filling in the large proglacial lake, a distance of some 800 m (2625 ft) (Ommaney 2002). Ommaney (2002) stated that "The glacier is not being surveyed regularly, so it is not known whether this advance is continuing." Aerial coverage and timing has been sporadic; thus, the need for a regular, systematic inventory of the glacier.

Traversing the glacier on a regular basis to monitor its changes is not logistically practical. The best means to routinely inventory and monitor the glacier is through satellite based remote sensing. In a 2011 study Baumann acquired 25 Landsat 5 data sets for the years from 1985 to 2010 and measured changes in the glacier. Except for 2005 a data set was obtained for each year. The selected images were taken between August 1 and September 19, the late summer-early fall period of the year. By this period the winter-spring snow had melted away, making it easy to distinguish the glacier from the surrounding land surfaces. All of the data sets were taken by the Thematic Mapper (TM) multispectral scanner on Landsat 5 and had a 30 m by 30 m pixel resolution.

This study found that the average annual rate of retreat between 1985 and 2010 was 111.97 m (367.26 ft.) but the rate varied from -58.44 m (-191.70 ft.) to 502.25 m. (1647.39 ft.) with a standard deviation of 118.74 m (367.26 ft.). Two of the years the glacier advanced but overall it was retreating. The glacier decreased in area from 2.45 sq. km. (.95 sq. mi.) to 1.52 sq. km. (.59 sq. mi.) in the 25 year period. At this rate of shrinkage the glacier might not be detectable in 25 to 35 years. The proglacial lake is larger than the glacier and growing in size as the glacier decreases. It will eventually extend up to the bottom of the icefall. Baumann's study is ongoing with imagery between 2011 and 2017 being acquired and studied.

Tennant and Menounos (2013) studied the 25 glaciers of the Columbia Icefield based on glacial drainage basins. They used the Interprovincial Boundary Commission Survey maps from 1919, eight sets of aerial photographs from 1948 to 1993, and satellite data from 1999 to 2009. They found that the highest rates of glacier retreat and shrinkage, and the highest rates of elevation and volume loss, occurred in the earliest period, 1919–48. Between 1970 and 1979 rates of change reached zero with some glaciers advancing in size. From 1979 to 1993, rates of elevation and volume loss again increased, before decreasing from 1993 to 2009. The rates of retreat and area loss varied, increasing during 1979–86, decreasing during1986 - 2000, and increasing to the highest rates during 2000–09. This study was based on the entire ice field and did not concentrate just on the Columbia Glacier.

HIGH RESOLUTION SATELLITE IMAGE

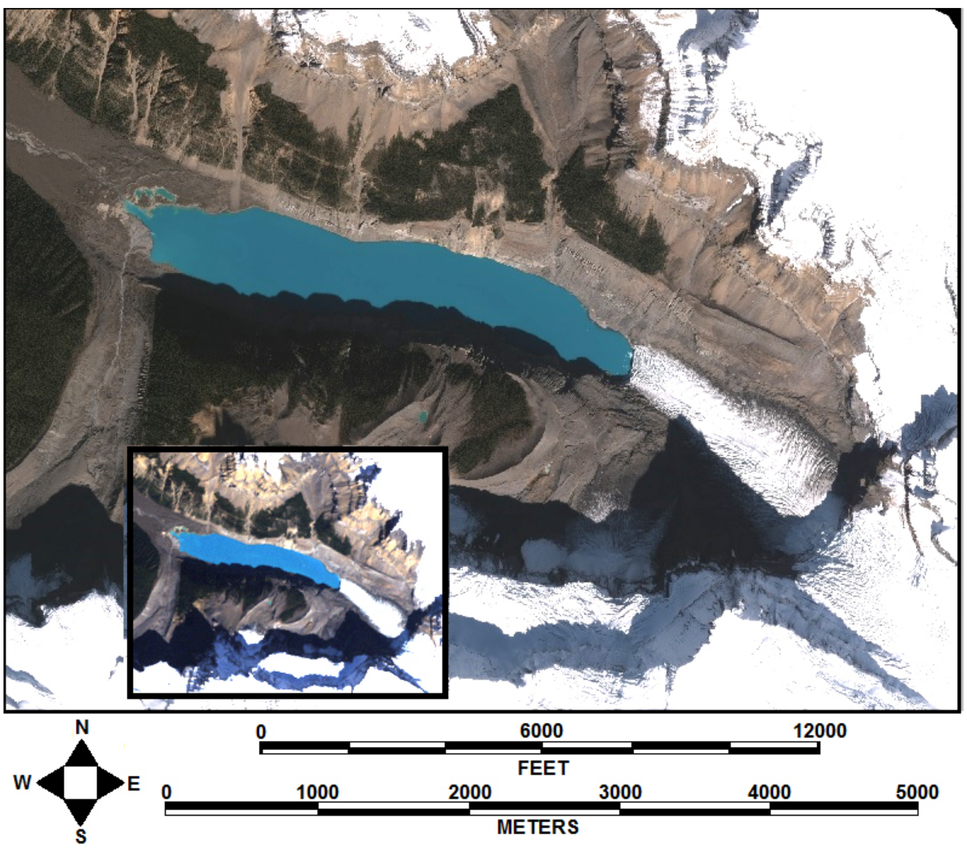

Figure 2: Columbia Glacier Basin (6.25% of full resolution).

Figure 2 is the high resolution satellite image showing the Columbia Glacier Basin. The image was taken by the Pléiades satellite 1A on September 21, 2016 towards the end of the ablation season. The image has a 50 cm (19.68 in.) by 50 cm (19.68 in.) pixel resolution. This resolution level should provide considerably more information about a place than the more common pixel resolutions ranging in size from 15 m (49.21 ft.) to 60 m (196.85) found on satellites like ASTER, Landsat, and Sentinel. Pléiades 1A's records in five spectral bands: 430–550 nm (blue), 490–610 nm (green), 510–580 nm (green), 600–720 nm (red), and 750–-950 nm (near-infrared). It was launched on

December 17, 2011 via a Russian Soyuz STA rocket out of the Guiana Space Centre, French Guiana and placed in orbit at 694 km (432 m). Its companion, Pléiades 1B, was launched on December 2, 2012. Pléiades imagery is distributed by the French agency Centre national d'études spatiales (CNES). In the United States Pléiades imagery can be acquired from Apollo Image Hunter. This image was purchased from Apollo Image Hunter and is not available in any other data repository.

This particular image is 15,715 pixels wide by 11,723 lines down. If printed at 300 dpi (dots per inch), the image would be 52.4 inches (133.09 cm) long and 39.0 inches (99.06 cm) wide. Thus, in context with this paper it is not possible to display the total image at full resolution. Most of the images presented in this paper show subareas of the full image, and most of these subarea images are not at 100 percent resolution. Not being able to illustrate these subarea images at their full size makes it difficult to convey to readers the detail provided by the image. In total ground size the image relates to an area of 7.85 km (4.88 mi.) by 5.86 km (3.64 mi) and covers 43.17 sq. km (16.67 sq. mi.). Its radiometric scale is 8-bits. It has zero cloud cover and is 9.2^{o} off-nadir.

The high resolution satellite image in Figure 2 is at 6.25 percent of its full resolution. As a comparison the inset shows a Landsat 8 image of the same area at 100 percent of its full resolution. The Landsat image was recorded on September 16, 2016, five days before the Pléiades 1A image was acquired. Both images are based on the three visible (red, green, and blue) bands recorded by each satellite. Even at 6.25 percent the high resolution image provides more detail than the Landsat 8 image at 100 percent resolution. Figure 2 provides a synoptic view of the basin. Based on this view the basin can be divided into three distinct but interrelated segments, namely the morainic terminus, the proglacial lake, and the glacier. The morainic terminus defines the foremost extension of the glacier within the last 300 years and contains outwash and recessional moraines. The proglacial lake occupies the bottom of a classical U-shaped valley carved by an alpine glacier. It receives water from the calving glacier and the annual snow melt from surrounding mountains. The lake is flanked by nearly vertical cliffs, 100 – 125 m (328 – 410 ft.) high that are dissected by steep gullies. As the glacier melts the lake continues to grow in length. The glacier descends 220 m (704 ft) from the Icefield down a spectacular icefall and is characterized by ogives and heavy crevassing. The center of the glacier is relatively free of debris and has a white surface. However, the glacier's northern and southern margins are heavily covered with supraglacial materials making it difficult to detect the edges of the glacier.

MORAINIC TERMINUS

The morainic terminus is the glacier's depositional area situated in front of the proglacial lake. This terminus is barely detectable on Landsat images as illustrated in the inset image in Figure 2. No terminal moraine exists on the outer edge of this terminus area but the trimlines formed by the glacier and the tongue-shaped pattern of the terminus outlines the farthest extent of the glacier (Figure 3). A 1955 study of 55 tree cores dated the maximum extent of the glacier at where the north trimline intersects the valley floor to approximately 1724 (Heusser1956). The earliest date found on the south trimline was 1763. A tributary glacier known as the Manitoba Glacier coalesces with the Columbia on its south side near the terminus. This glacier along with the south side of the Columbia being in the shadow of the mountains throughout most of the year may have delayed the ice retreat. Both dates correspond to the end of the Little Ice Age. The tree core study also identified four recessional moraines on the terminus, dated 1871, 1907, 1909, and 1919. However, the satellite image shows three recessional moraines. It is possible that the 1907 and 1909 moraines are the same. No map identifying the moraines by date was provided. Approximately 125 years passed between farthest extension of the terminus and the development of the first recession moraine suggesting that the glacier was stationary between the mid-17 hundredths and 1871or retreating very slowly. The 1919 date for the most recent moraine relates to the earlier mentioned 1924 oblique aerial photograph that shows the front of the glacier located at the back edge of the terminus and no proglacial lake.

The Athabasca River flows across the terminus draining water from the proglacial lake. The satellite image shows a naturally made dam at the point where the river starts (Figure 4). Mist can be detected in front of the dam. The numerous river rapids indicate a steep gradient as the river descends the terminus. Beyond the terminus the river widens on the valley floor and has fewer rapids (Figure 3). It has a well-defined flood plain, likely formed by the variable seasonal discharge associated with the ablation process.

Prevailing westerlies winds with moist Pacific air nourish the icefield and adjacent areas, especially during the winter season. These winds bring substantial amounts of snow to the Columbia Glacier Basin (Lunar and Planetary Institute, 2003). With steep mountain slopes outlining the proglacial lake, a large amount of the snow washes down into the lake particularly during the spring. This additional water in the lake can place considerable pressure on the previously mentioned dam. A dam failure would result in outburst flooding in the valley below. The two small lakes located on the terminus near the mouth of the proglacial lake appear to be water-filled kettles.

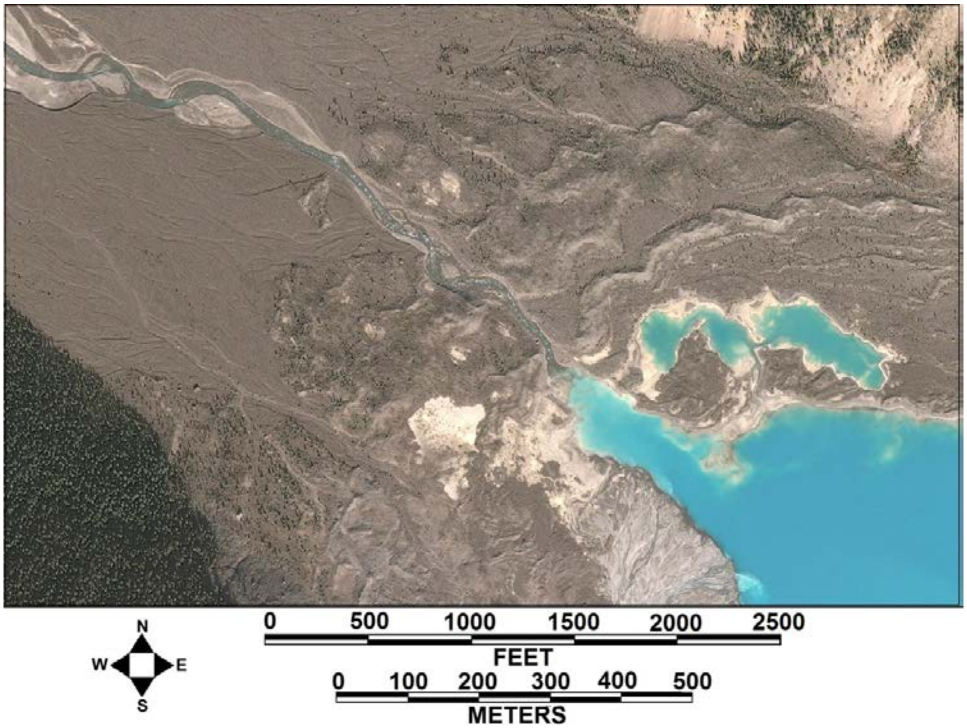

Figure 3: Terminus Area (25 % of full resolution).

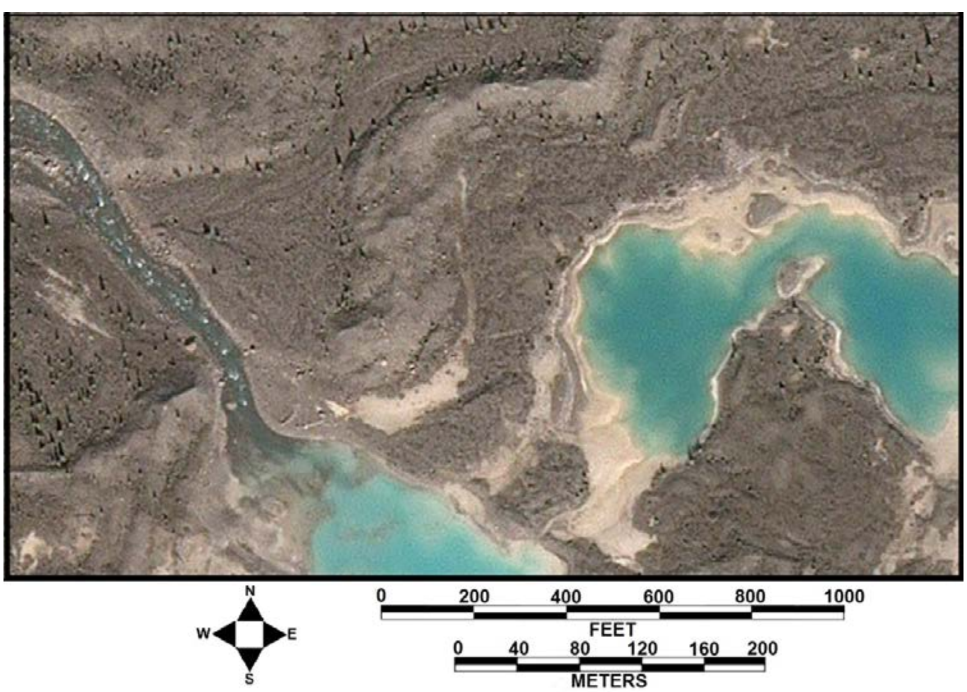

Figure 4: Athabasca River with falls and portions of two recessional moraines (100 % resolution).

As illustrated in Figure 3 the area below the terminus is covered by low lying vegetation that forms a continuous mat on the valley floor, laced with small shifting streams. The vegetation patterns indicate that the valley floor is relatively flat. Few trees exist here and those that do occur on the valley edges. Seeds must come from the adjacent tree-covered slopes. On the terminus, trees do not appear on the recessional moraines (Figure 4). They are found widely spaced along the edges of the moraines. In between the moraines, low lying vegetation grows in mats similar to what is found on the valley floor below the terminus. The lack of trees might relate to the strong cold winds that flow from the ice field down over the glacier and through the valley. The trees on the terrace slopes are predominately evergreen. Larger and healthier appearing trees exist on the slopes than on the valley floor and the terminus. They also grow in greater density. As the image was captured during the fall season the brown color of the vegetation on the valley floor and the terminus suggests that the vegetation is predominately deciduous in nature.

PROGLACIAL LAKE AND TRIMLINE

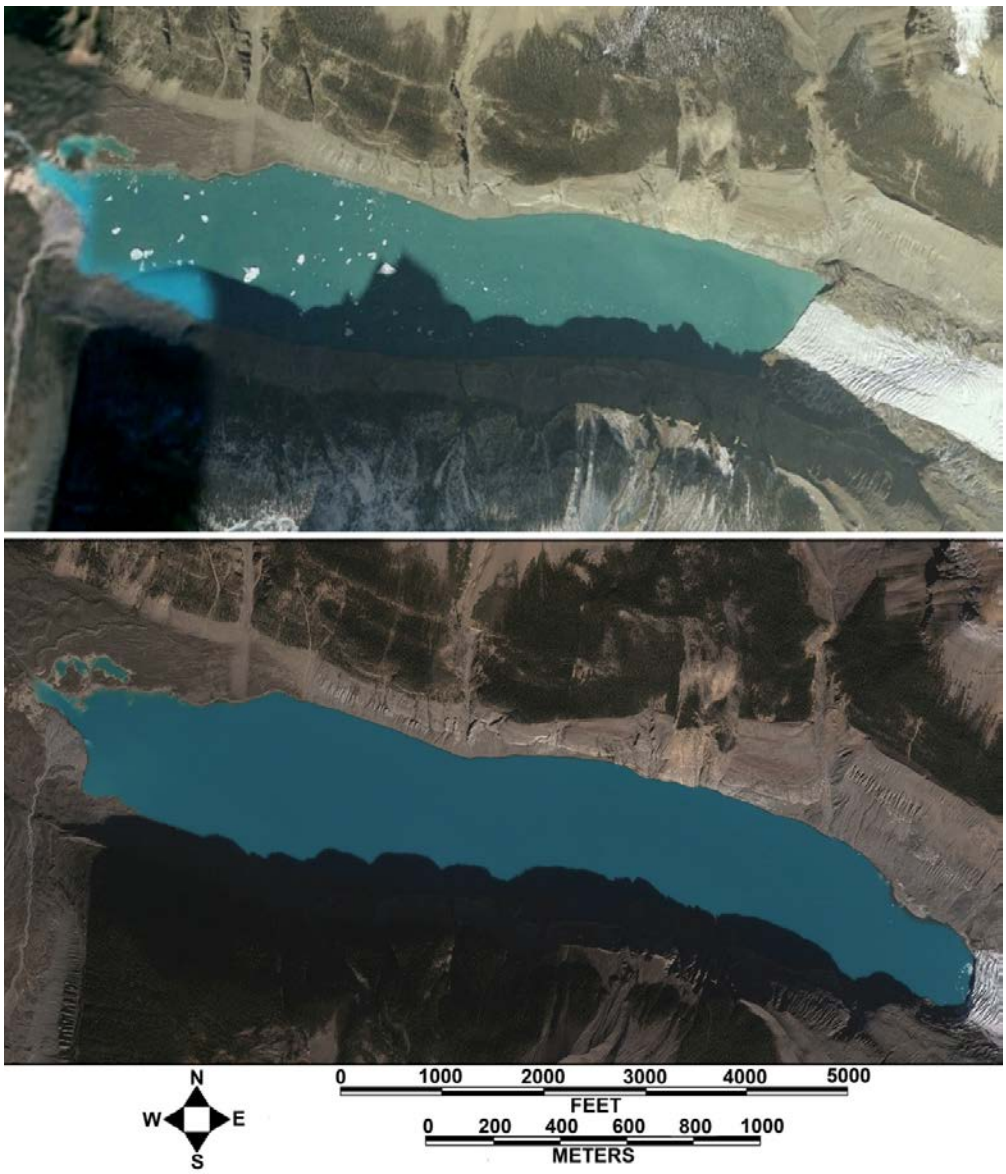

Figure 5: Proglacial Lake in 2004 (top) and 2016 (bottom, 12.5 % of full resolution).

The proglacial lake is 4.27 km (2.65 mi) in length and averages about .57 km (.36 mi) across. It is large when compared to other such lakes associated with the Columbia Icefield. Some of the outlet glaciers have no proglacial lakes, and of those that do, the lakes are quite small even though their respective glaciers are much larger than the Columbia Glacier. This lake, held in place by the morainic terminus, is a reservoir of fresh water. In addition to being fed by the glacier and snow fall, several streams flow into the lake. Most of these streams are intermittent based on snow melt in the surrounding mountains. Two streams on the north side of the lake flow continuously. One comes from a south facing cirque that has enough snow to maintain flow year around and the other from a small glacial basin where the glacier no longer exists but the basin is high and cold enough to contain snow the entire year. In the latter situation the basin shows no surface snow during the fall season when this image was taken but probably has snow in the porous glacial debris. The amount of water from this stream likely vacillates throughout the year. Two annual streams flow into the lake from the south side. One comes from the Manitoba Glacier. This stream enters the lake near where the Athabasca River starts, and thereby, most of its water flows out of the lake rather quickly. The Manitoba Glacier is not part of the Columbia Icefield but is fed by cirques. It has a supraglacial surface of rock fragments and a well-developed delta. The second stream comes into the lake near the glacier's present snout; unlike the Manitoba Glacier stream water from this stream moves almost the entire length of the lake before entering the Athabasca River. On the east side of the Columbia Glacier, near its icefall, a series of separate, small icefalls exist dropping from the ice field. Below these icefalls the land is covered with rocky debris. Water flows through this debris to form the stream. This entire area was once part of the base section of a much larger Columbia Glacier. A 2004 high resolution image, available from Google Earth, shows more ice/snow coving this area than the 2016 image (Figure 5). (The 2004 image, taken on September 23 only two days apart from the 2016 image, provides high resolution over most of the lake and the glacier but the terminus and the west end of the lake is shown in a lower resolution. Imagery from two different resolution levels were mosaic together. The high resolution portion of the 2004 image is not as sharp as the 2016 image. Also, the shadows over the lake suggest that the 2016 image was taken around noon; whereas, the 2004 image was recorded in late afternoon.)

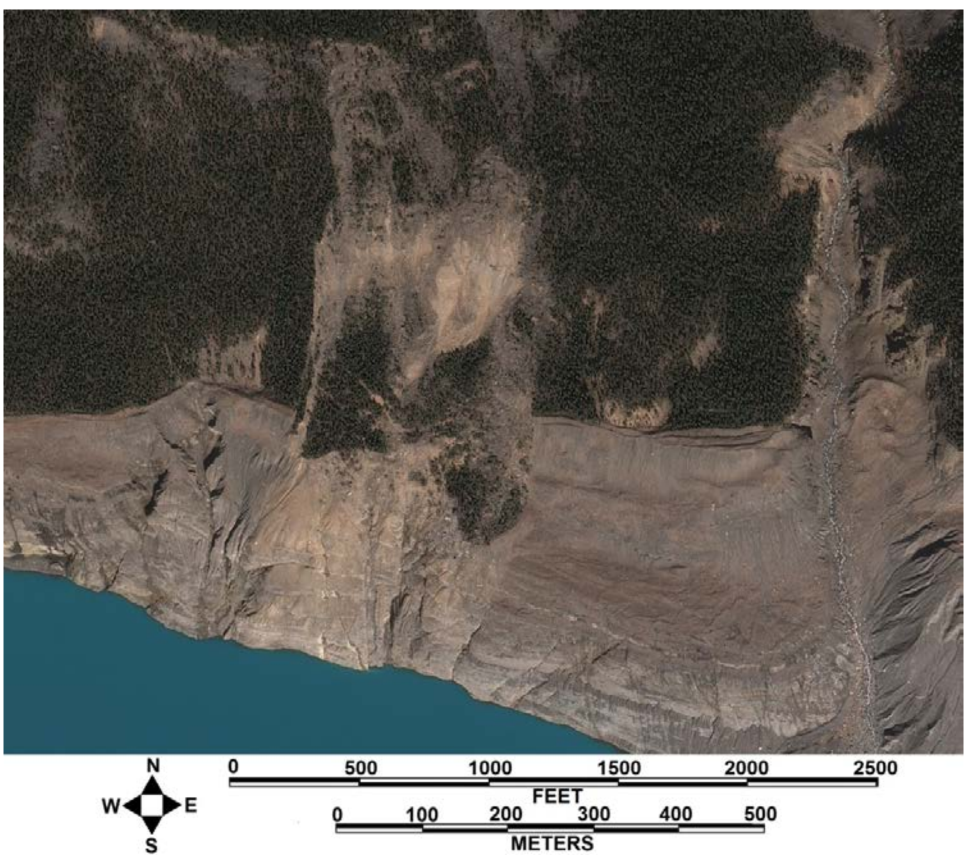

Figure: 6: Proglacial Lake and Landslide (25 % of full resolution).

The lake's surface area covers 238.4 hectares (589 acres). Without depth information it is not possible to determine the volume of water in the lake and with the glacier continuing to recede, the lake's volume and surface area keeps increasing. Although the lake's depth is not known, it appears that it might be deep. Bare bedrock walls exist along most of the periphery of the lake, a product of the glacier's forward, cutting movement. The walls appear to continue straight down into the water, not permitting any shoreline build-up of beach sediment. Mountain shadows on the lake's south side make it harder to interpret the bedrock walls but with some minor image enhancements the walls can be seen and they are merging into the lake, at a steeper angle than the walls on the north side. The lake's bottom most likely has a U-shape profile, typical of many glacial valleys.

A number of landslide scars appear on the north side of the lake. Figure 6 shows a large landslide where a section of the evergreen forest shifted, intact, down slope. Based on the new location of these evergreen trees and where they were before the landslide, the land dropped between 160 m (527 ft) and 185 m (613 ft). The color difference in the surface material suggests that the slide went into the lake but in comparing the strata patterns between the slide and non-slide areas, the eastern portions of the landslide did not slip down into the lake. Conditions on the west side of the slide are too complex to know if this section reached the lake.

On the north side a lateral moraine parallels the trimline with the evergreen forests situated just above the moraine (Figures 5 and 6). The slope above the trimline is not as steep as it is below the line. Above the trimline the land was not glaciated over the last 300 years allowing for forest conditions to develop. The moraine is intersected by landslides and small stream valleys. It gradually diminishes in height moving down valley and becomes barely perceptible. The moraine continues above the glacier's present snout identifying the glacier's side shrinkage.

GLACIER AND ICEFALL

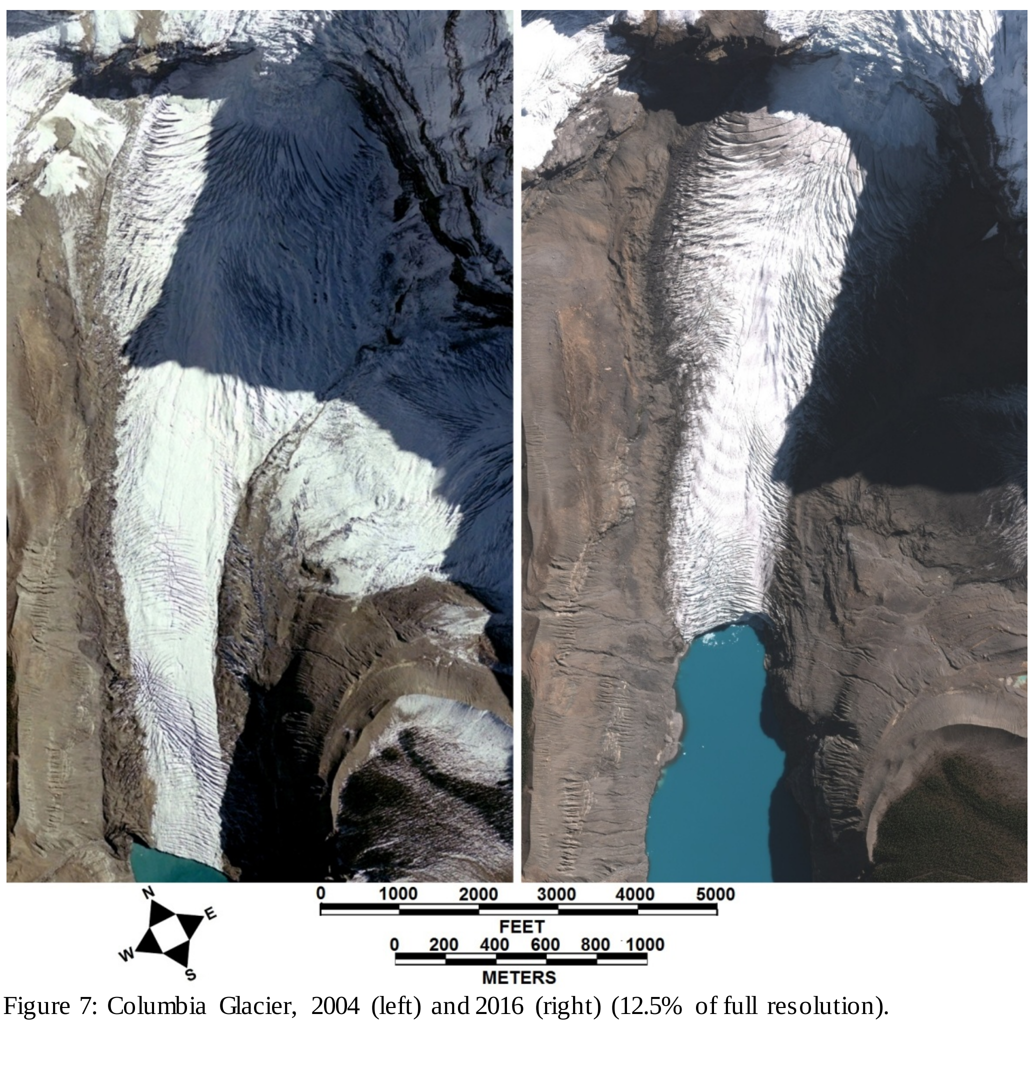

Figure 7: Columbia Glacier, 2004 (left) and 2016 (right) (12.5% of full resolution).

A large lateral moraine exists on the north side of the valley. It parallels the present day glacier and stretches in a linear pattern up to the plateau wall (Figure 2). A similar moraine occurs on the south side of the valley but it is arranged in a sharp, curvilinear pattern from the wall down toward the lake. These two moraines mark the farthest that the glacier extended across the base of the plateau, 5.89 km (3.66 mi.). The glacier was broad and massive at this point in time and it most likely flowed from the ice field rather than dropping over the plateau edge as an icefall. Today the glacier is .4 km (1/4 mi.) across the base of the plateau and has a 220 m (704 ft.) icefall.

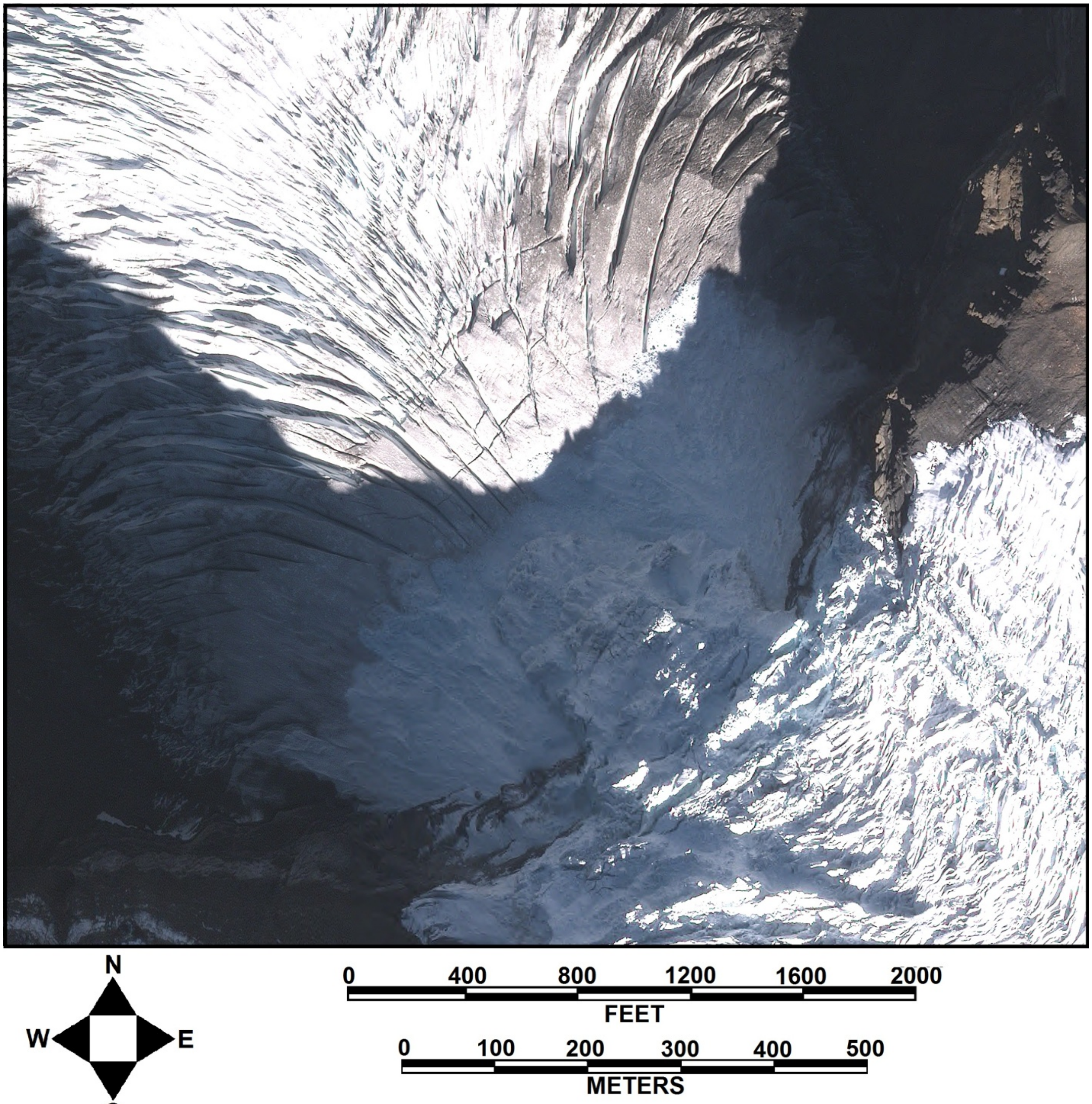

Figure 8: Ice Fall (50 % of full resolution).

A small amount of calving is evident in Figure 7. Ice blocks appear immediately in front of the glacier but the remainder of the lake is relatively free of such blocks. The 2004 high resolution image shows a great number of large ice blocks concentrated at the lower half of the lake. Since both images were taken in September, two days apart, it is not clear as to why the proglacial lake has so many ice blocks in 2004 in comparison to 2016. A crevasse field runs across at the front of the glacier. The crevasses are aligned as if they were preparing to be calved. The 2004 image shows two crevasse fields separated by a narrow band of rather smooth ice. In the 2016 image the first 2004 crevasse field along with the band of smooth ice is gone due to the melt back and calving of the glacier. At this rate of change the back zone which is now at the front of the glacier might be gone in ten to twelve years. A series of ice waves, known as ogives, runs down the center of the glacier. Ogives are alternating ridges and swales that appear as light and dark bands of ice on a glacier's surface. The ridges are light in color while the swales are dark. Ogives are linked to the seasonal motion of a glacier; the combined width of one dark and one light band generally equals the annual movement of the glacier. Figure 7 shows eleven combined swales and ridges. The swales form from ice that flows over the ice fall during the summer and the dark ridges from ice that moves over the fall in the winter. Ogives bend down-glacier due to the faster flow in the center of the glacier than along the sides of the valley walls. Being able to observe and measure these ogives could provide a great amount of information about the life span of the glacier.

Figure 8 is a rather dramatic view looking down the icefall from the ice field. A large mound of ice has dropped from the ice field down onto the glacier. This dropping process appears to have formed a fan-shaped, bursting pattern of crevasses (Figure 8). Surrounding the mound of ice is a white colored surface followed by a dirty colored ring. This might be the development of a new ogive. If so, the white ring represents ice from the 2016 summer and dark from the preceding winter. The image was taken in the early fall season of 2016. Both rings are rather large compared to the established ogives. If the glacier melts completely and the lake expands up to the base of the plateau, the question must be raised, "Will a large amount of ice dropping down the icefall onto the lake form a tsunami type wave resulting in a rupture in the natural dam on the morainic terminus, and thereby, the draining of the lake and creating a massive flood down the Athabasca Valley?" Concern already exists about landslide-generated tsunamis in the mountains of the Pacific Northwest (Kafle 2016).

SUMMARY

This image has provided more new information about the Columbia Glacier Basin than had been previously recorded. Additional information will be ascertained in the future as the image is studied in greater detail and other remote sensing techniques are applied. Two areas that need further study are the north facing slope on the south side of the lake and the depth and bottom of the lake. The north facing slope is partially hidden by shadows mainly from Mount Columbia. The image can be enhanced by using different spectral bands to expose the shadowed areas but not enough to provide the detail as recorded on the south facing slope. It might be necessary to take oblique aerial photos looking directly at the north facing slope to obtain the needed information. The image is not designed to penetrate water to any great depth. The depth and the bottom of the lake need to be known in order to determine the volume of water in the lake, and thereby, ascertain how large of a freshwater reservoir exists with the lake. The best means for gaining this information is using a LiDAR (Light Detection and Ranging) sensor. A LiDAR flight is expensive and as the lake grows due to glacial melt back additional LiDAR flights will be needed. With respect to monitoring change in the basin a new high resolution image taken every five years should be sufficient. However, within five years such imagery will have a 5 cm pixel resolution making for an image that will be ten times larger than the present image at 50 cm. Within the five year interval, Landsat can be used to record basic annual changes such as the melt back of the glacier and the expansion of the lake. A Landsat inventory of the basin that extends over 32 years already exists and this inventory will continue with the existing Landsat 8 and the scheduled launches of Landsat 9 and Landsat 10 in 2020 and 2027, respectively.

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