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Structural Elements in the Alberta Plains

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Structural Elements in the Alberta Plains

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Abstract

Resource exploration in Alberta is critically related to knowledge of the location and age of structural features, particularly faults, which may have created hydrocarbon traps, acted as pathways for mineralizing fluids, or facilitated kimberlite emplacement. Moreover, natural fault locations are of paramount importance for public safety and environmental protection. Over the years, the Alberta Geological Survey (AGS) has studied the stratigraphic framework of the province and corroborated its own stratigraphic and structural data with relevant information published by both industry and academia in order to aid government and industry in their efforts to ensure responsible development of oil, natural gas, oil sands, geothermal, groundwater, and coal resources. This report presents the AGS's effort in acquiring structural data in the subsurface of the Alberta Plains (e.g., faults, shear zones, arches, escarpments), and offering the data to the public as an interactive web application. The web application comprises a province-wide compilation of structural features observed or inferred by different workers through different methods at different structural and stratigraphic levels, from the crystalline basement to the surface. Lineaments from various literature sources (digital and nondigital) were geospatially referenced, compiled digitally into Esri shapefiles, and individually tagged with attribute data stored in a database (also accessible on the AGS website). This report summarizes the compilation workflow and includes a succinct overview of the structural framework of the Alberta portion of the Western Canada Sedimentary Basin, in order to facilitate understanding of the geological significance of the compiled structural features with respect to the overall architecture of the basin.

1 Introduction

Locations of natural faults in the province are of paramount importance for public safety, environmental protection, and estimating the potential of a variety of resources including petroleum, metallic minerals, groundwater, and geothermal. Stress accumulating on natural faults may suddenly be released naturally as shear slip, resulting in earthquakes, or may be triggered by anthropogenic activities (wastewater disposal, reservoir impoundment, hydraulic fracturing, resource extraction), resulting in induced seismicity. Exploration for a wide range of deposits is critically dependent on knowledge of the location and age of fractures, which may have created structural hydrocarbon traps, acted as pathways for mineralizing fluids, and facilitated kimberlite emplacement.

Although regional structures, and their controlling faults, in the Alberta Plains have been reasonably well documented in the subsurface by the oil and gas industry, no detailed publicly available structural synthesis exists. The present compilation of subsurface and surface tectonic and structural features (e.g., faults, shear zones, arches, escarpments) provides a tectonostratigraphic and structural framework of the province that is readily accessible to the public as an interactive web application at https://ags-aer.maps.arcgis.com/apps/webappviewer/index.html?id=38f3fc41840e4d94b6834d8995705225. The compilation of faults documented in the geological literature needs, however, to be supplemented with structural-stratigraphic studies in areas of interest and/or inconclusive data.

The first part of this report comprises an explanation of the digital compilation work delivered as a web application, whereas the second part provides a brief overview of the tectonostratigraphic evolution of Alberta in order to facilitate understanding of the geological significance of the compiled tectonic and structural features.

2 Compilation Method

2.1 Data Sources

The new compilation, at the scale of the province, builds on the initial work by Pană et al. (2001). This work was limited to northern Alberta and included the examination of structures extracted from approximately 300 sources published between 1958 and 2000. The *Geological Atlas of the Western Canada Sedimentary Basin* (Mossop and Shetsen, 1994), published by the AGS, served as the framework of the geological explanations in the report.

In this new version, structural features from various geological reports published between 2001 and 2018 have been added and all issues of the Bulletin of Canadian Petroleum Geology and the American Association of Petroleum Geologists (AAPG) Bulletin published between 1953 and 2017 have been systematically searched.

2.2 Workflow

Pană et al. (2001) describe the GIS compilation workflow used for this project in detail. In summary, the structural features from each source were digitized and georeferenced into Esri shapefile format. Each set of features from a given source was tagged with an estimate of its positional accuracy, based on the root mean square (RMS) error reported during georeferencing. Each individual feature in the set was assigned descriptive geological attributes, using both ArcGIS and Microsoft Access to view and capture the information.

2.3 Positional Accuracy

Pană et al. (2001) also discuss the accuracy and precision of natural resources data. It is worth restating that the spatial features in the compilation are not as spatially accurate as their computer precision would suggest. This means that although features appear to be located with submetre accuracy, various factors have contributed to the degradation of the final positional accuracy, including mapping errors by the original author, georeferencing errors (especially from scanned, paper-based sources), and subsequent digitizing. Users of the data should note the error range associated with each feature (ERRRANGE attribute) and should consult the original reference as appropriate.

3 The Web Application

The primary purpose of the web mapping application is to provide easy access to the compilation of structural-elements spatial data (in vector format) in an interactive web-based environment. The users can visualize the spatial data at various map scales, run queries, build on the available attributes, and extract subsets of vector features in different file formats or in a tabular form without any advanced knowledge of GIS technologies. There is no requirement to install and maintain GIS capable software on a local device unless deemed necessary to facilitate more complex spatial analyses.

The scalability and the ability to configure the web mapping application and expand its functionality as needed in real-time make it, in many regards, the first choice of tool to explore and analyze the data.

The information about the data source, in many instances provided on a feature-by-feature basis in the attribute table, allows users to investigate the data further and, if needed, add additional vector layers to the application and create custom-made map mashups tailored to the user's needs and likes.

The digital format provides a flexible structure capable of incorporating additional information and allows various options for data selection based on query criteria such as location, timing, orientation, and authorship. The web application allows for continuous updates and refinements. Time constraints required the careful selection and prioritization of sources to be converted to GIS format. Consequently, the user should be aware that there are structures that have been described in the geological literature but have not been included in the database. More importantly, it must be realized that the density of the structural features does not necessarily reflect the structural complexity of a certain area, but rather the present level of knowledge. The density of wells and published geological information throughout Alberta is highly uneven. For example, well coverage is quite good in northwestern Alberta and very good in north-central Alberta due to past and present hydrocarbon exploration, whereas the northeastern part of the Western Canada Sedimentary Basin (WCSB) has poor well coverage. Nevertheless, the authors are confident that all significant structural features in Alberta documented or inferred in the open literature up to 2018 have been captured.

Compiled structural features are available on the AGS website in a user-friendly format. The major tectonic and structural features (‘Selected tectonic features’) are represented on a simplified geological map of the province (Figure 1; also offered on the AGS website as a page-size .pdf file) derived from the AGS’s *Bedrock Geology of Alberta* map (https://ags.aer.ca/publications/MAP_600.html). Zooming in, the captured lineaments are separated into two main layers: ‘Surface lineaments’ and ‘Subsurface lineaments’, which are represented on a surficial topography map (the digital elevation model [DEM] was derived from light detection and ranging [LiDAR] images) and on the *Bedrock Geology of Alberta* map, respectively. Included are compilation faults interpreted by different oil and gas operators based on their seismic studies and provided to the Alberta Energy Regulator (or its predecessors), as well as surface and subsurface lineaments tentatively interpreted by the first author to be structurally controlled, specifically

- lineaments derived from facies and/or thickness changes depicted on maps in the *Geological Atlas of the Western Canada Sedimentary Basin* (Mossop and Shetsen, 1994), and
- surface lineaments derived from LiDAR images and added to lineaments compiled from aerial photographs and satellite imagery.

The web application layers display mapped igneous rocks (‘Intrusions and volcanics’, including Cretaceous kimberlites in central and northern Alberta, Eocene ultrabasic intrusions in southern Alberta, and dikes and sills in the Rockies) and impact structures (‘Astroblemes’) documented or inferred in the Alberta Plains.

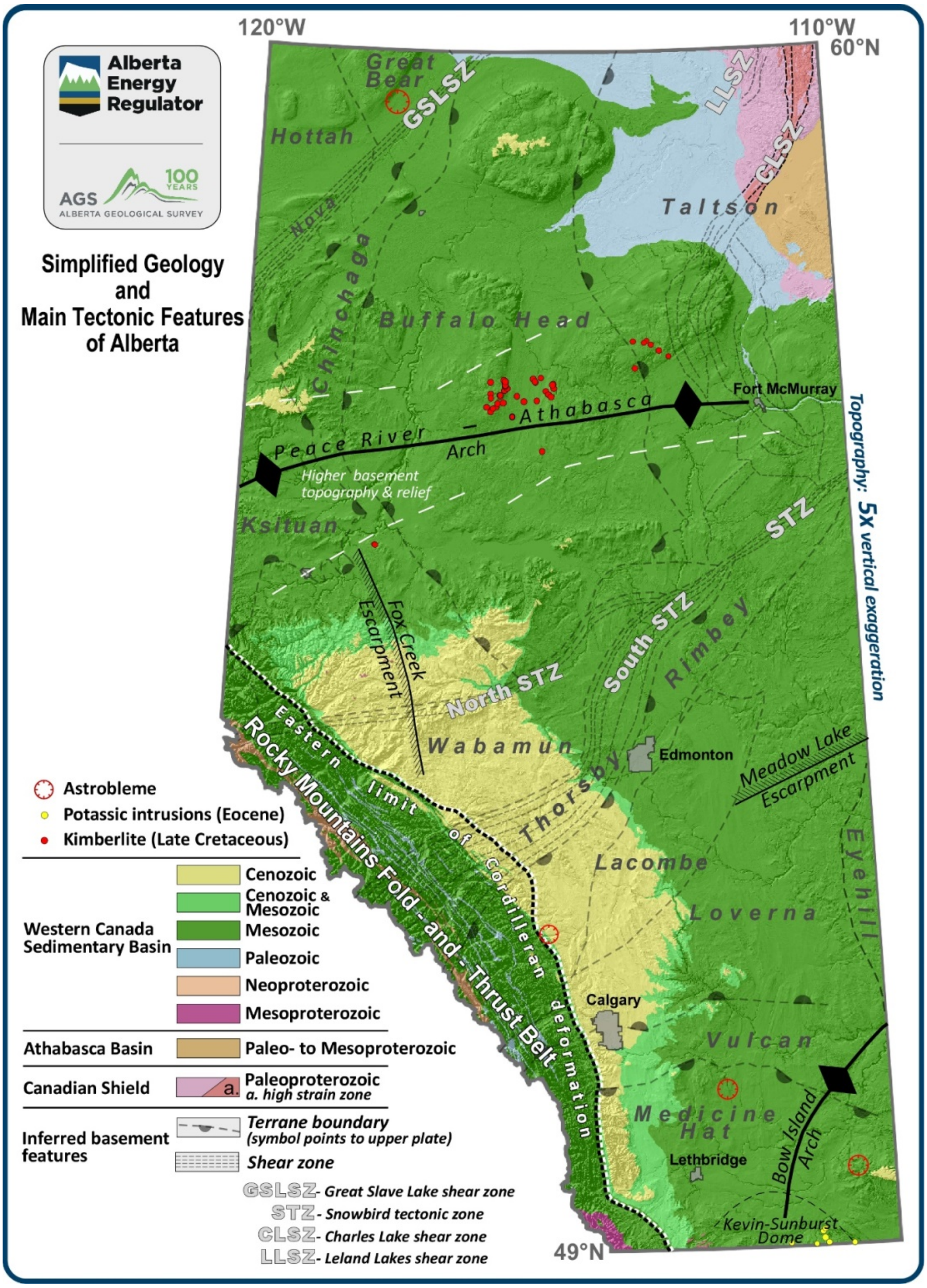

Figure 1. Simplified geology and main tectonic features of Alberta. The separation of domains of distinct magnetic fabric in the crystalline basement combined with U-Pb geochronology and Sm-Nd isotope geochemistry of basement drillcore, and LITHOPROBE seismic studies led to the current interpretation of the Alberta basement as tectonic domains involved in the late Paleoproterozoic assembly of western Laurentia (see text). Archean provinces are abbreviated: Nova (a slice of Slave Province); Loverna, Eyehill, and Medicine Hat (blocks of Hearne Province) separated by Vulcan magnetic low - a complex and controversial structure (rift versus collisional zone) of inferred Paleoproterozoic age. Proterozoic terranes (2.4–2.0 Ga) are abbreviated as: Chinchaga, Buffalo Head, and Wabamun; Thorsby is a remnant of Proterozoic oceanic lithosphere. Paleoproterozoic (2.0–1.8 Ga) continental magmatic arcs are abbreviated: Ksituan, Taltson, and Rimbey, south of GSLSZ, and Hottah overprinted by Great Bear, north of GSLSZ; Lacombe was interpreted as a Proterozoic metavolcanic rocks sequence.

The current compilation may require more focused stratigraphic and structural analysis in selected areas and/or stratigraphic intervals in order to delineate the extension of previously known faults or discover new faults. The benefit of the current compilation in GIS form is that new data can be easily integrated into the existing digital database.

4 Lithotectonic Assemblages of Alberta

The present structural compilation encompasses the Alberta Plains, east of the Rocky Mountain Foothills. Geologically, most of the Alberta Plains are underlain by sedimentary rocks of the Phanerozoic Western Canada Sedimentary Basin (https://ags.aer.ca/publications/MAP_600.html) and, in the northeastern part, by strata of the Proterozoic Athabasca Basin (https://ags.aer.ca/publications/ MAP_537.html and MAP_538.html). The floor to these long-lived sedimentary basins is a crystalline basement, represented by a collage of variably recycled Archean and Paleoproterozoic terranes welded together between 1.9 and 1.8 Ga during the assembly of Laurentia (Hoffman, 1988, 1989; Ross et al., 1994a; Ross, 2002).

The current understanding of the Proterozoic accretion of crustal slivers that form the Alberta basement and of the subsequent basin evolution benefited greatly from the national LITHOPROBE program (1984–2003), which was conducted to extend knowledge of the continental lithosphere in Canada into the third dimension, depth. In Alberta, this multidisciplinary (geophysical, geological, and geochemical) research program was spearheaded by seismic reflection surveys acquired between 1992 and 1995, with the results and interpretations published up to 2002. The location of each LITHOPROBE seismic line in Alberta is included in the web application and can be compared to the structural features compiled in the Alberta Plains. The 1994 Peace River Arch Industry Seismic Experiment (PRAISE) was a regional reflection seismic survey, whose results built on the previous refraction experiment recorded in 1985, and was designed to characterize the crust beneath the Peace River Arch (Stephenson et al., 1989; Zelt and Ellis, 1989). The PRAISE survey focused on the seismic patterns in the sedimentary section, and collected a total of 654 km of seismic reflection data in nine different line segments (lines 11–20) across crustal domains in north-central Alberta (e.g., Ross and Eaton, 2002). The southern end of the PRAISE program linked up to the northern end of the 1992 Central Alberta Transect (CAT) program (Ross et al., 1995, Ross and Eaton, 2002). The Southern Alberta Lithospheric Transect (SALT) 1995 data offered the opportunity to study the structural styles of the Western Canada Sedimentary Basin (WCSB) to the Rockies, as it extends from the plains of southeastern Alberta to the triangle zone in the Foothills. The SALT lines 29, 30, and 31 include 290 km of seismic reflection data; SALT lines 30 and 31 extend west-east (for 110 and 140 km, respectively), whereas line 29 is a north-south tie line (40 km long), creating sparse, regional, three-dimensional (3D) coverage (Eaton and Ross, 1996; Lamieux, 1999).

This report includes a review of the crustal components and tectonics during the late Paleoproterozoic assembly of Laurentia including major basement structures such as Proterozoic shear zones, Phanerozoic arches, and hinges that may have influenced sedimentation patterns. Major tectonic and structural elements are represented on the tectonic map (Figure 1) and attributed faults are available in the associated web application. Spatial relationships between structures and kimberlite pipes or mineral occurrences in northern Alberta have been discussed in Pană et al. (2001).

4.1 Crystalline Basement

Crystalline basement is only exposed in relatively limited areas of northeastern Alberta, north and south of the Athabasca Basin (Pană, 2010a). Processes and resulting structures in the basement are reflected in mantle-controlled patterns of sediment accumulation both in the craton interior (Athabasca Basin) and at the craton margin (WCSB; Bond and Kominz, 1984; Beaumont et al., 1993; Price, 1994; Eaton et al., 1995; Hope et al., 1999; Ross and Eaton, 1999). The mosaic of inferred crustal slices and their relationships (Figure 1) is briefly reviewed in Section 5.

4.2 Athabasca Basin

The Athabasca Basin has a dish-shaped outline, with an east-west long axis, which straddles the Alberta–Saskatchewan border; only about 100 km of its western extent exists in northeastern Alberta (Figure 1). Sedimentary rocks of the basin crop out south of Lake Athabasca, in a few islands of the lake, and along its northern shore. The dish shape of the Athabasca Basin suggests its formation by a broad thermal subsidence mechanism unrelated to the Proterozoic orogens documented in the adjacent basement. It can be viewed as a postorogenic intracontinental sag basin with four sub-basins filled between ca. 1740–1730 Ma and 1500 Ma by four unconformity-bounded quartzose fluvial sequences, each with distinct grain-size distributions and paleocurrent directions (Ramaekers et al., 2007). These sequences form the Athabasca Group with an aggregate stratotype thickness of 3800 m, of which much has been eroded and the preserved thicknesses of individual lithostratigraphic units vary laterally (Ramaekers et al., 2007). The youngest detrital zircon in the oldest unit is 1815 Ma, but coexisting monazite and titanite have ages of 1775 and 1750 Ma, which indicate that the initiation of deposition in the basin occurred 10–20 million years later, time necessary for the uplift and exhumation of monzanite-bearing basement rocks and their exposure to erosion (Orrell et al., 1999; Annesley et al., 2005; Rainbird et al., 2007). Organic matter from black mudstone of the Douglas Formation in the upper part of ‘sequence 4’ (upper Athabasca Group) has been dated at 1541 ±13 Ma by Re-Os geochronology (Creaser and Stasiuk, 2007).

The eastern Athabasca Basin contains the world-famous Athabasca unconformity-type uranium deposits. These are amongst the richest uranium deposits in the world and occur near the interface (unconformity) between the late Paleoproterozoic to Mesoproterozoic Athabasca Group and the crystalline basement, exclusively in the upper portion of commonly graphite-bearing basement shear zones and their immediate Athabasca Group sandstone cover (lid; Pană, 2007). In the Alberta portion of the Athabasca Basin, a uranium prospect of this deposit type exists at Dragon Lake along the Maybelle shear zone that overprints ca. 1.97 Ga granitoids (Stern et al., 2003). A series of articles on various aspects of the Athabasca Basin geology can be found in Jefferson and Delaney (2007).

4.3 Western Canada Sedimentary Basin

The WCSB includes strata of Mesoproterozoic to Cenozoic age and thickens from an erosional zero edge in the northeast to more than 20 km within the Cordillera. Farther west, the WCSB extends to a series of margin-parallel sub-basins along the western edge of the North American craton (e.g., Struik, 1987). In the present configuration of the Canadian Cordillera, tectonically dispersed remnants of the Slide Mountain back-arc basin mark the boundary between the North American autochthonous rocks and the allochthonous terranes. To the east, the WCSB comprises two major sedimentary basins (Alberta and Williston) separated by a broad northeast-trending positive element, which includes the Bow Island Arch and the Swift Current Platform. The western elongated Alberta Basin is situated in front of the Canadian Cordillera, and the eastern subcircular intracratonic Williston Basin is centred in North Dakota and extends into southern Saskatchewan and southwestern Manitoba.

In general, the pre-Mesozoic deposition in the WCSB is interpreted to have taken place in a passive margin tectonic setting, although the western margin of ancient North America is considered to have been convergent since the Middle Devonian (e.g., Monger, 2014). A phase of active tectonism, related to the Antler orogeny documented in the United States segment of the Cordillera, has been proposed along the western margin of the WCSB with consequences on Late Devonian–Mississippian depositional processes and basin geometry (e.g., Root, 2001; Henderson et al., 2009; Johnston et al., 2010).

Mesozoic Cordilleran tectonothermal events complexly deformed and metamorphosed Proterozoic to early Paleozoic strata of the western margin of the WCSB. Proterozoic to Cenozoic strata of the WCSB were incorporated in the Late Jurassic to early Eocene Rocky Mountains fold-and-thrust belt (McMechan and Thompson, 1989, 1992; Price, 1994; Pană and van der Pluijm, 2015). East of the fold-and-thrust belt, the sedimentary cover underlying the Alberta Plains ranges in age from Middle Cambrian to Cenozoic, a stratigraphic record of ~500 million years. The tectonic loading of the North American craton by the encroaching fold-and-thrust belt triggered the downwarping of the North American lithosphere (Price, 1973, 1994), which greatly affected the evolution of the entire WCSB. Thus, the tectonic setting of the WCSB gradually evolved from passive margin to a tectonically active foreland basin during the Triassic in the northern Canadian Cordillera (e.g., Nelson et al., 2006; Beranek and Mortensen, 2011) and during the Early Jurassic at the latitude of present-day Alberta (Pană et al., 2018a, b).

This structural compilation encompasses the Alberta Basin within the province of Alberta. Geologically, the northern limit of the Alberta Basin is immediately north of the Alberta boundary and is represented by the subtle and ephemeral Tathlina Arch in the Northwest Territories, whereas the southern limit is the Sweetgrass Arch of Montana, with its northern extension known as the Bow Island Arch in southeastern Alberta (Figure 1).

5 Crystalline Basement of Alberta

5.1 Early Proterozoic Evolution and Basement Structures

The Alberta basement is the western continuation of the Canadian Shield, which lies buried beneath the Proterozoic Athabasca Basin and the Phanerozoic sedimentary rocks of the WCSB. Its evolution has been inferred based on potential-field data (magnetic and gravity) and U–Pb dating of drillcore, and by extrapolating data from the exposed and better understood Canadian Shield elements to beneath the sedimentary cover (Hoffman, 1987; Ross et al., 1991, 1994a; Villeneuve et al., 1993; Leclair et al., 1997; Boerner et al., 2000; Burwash et al., 2000; Pilkington et al., 2000; Ross, 2002; Ross and Eaton, 2002). A compilation of prior data for the northern half of the province, including locations of basement core, and petrological, geochemical, and geochronological data, can be found in Pană (2002). The last tectonic synthesis of the evolution and assembly of the crust and lithosphere in Alberta integrated “geophysical and geological studies at a range of scales from the uppermost crust exposed in northeastern Alberta to upper mantle imaged in teleseismic and controlled-source seismic experiments” (Ross, 2002, p. 414). In this report, only a brief review of the basement domains and structures and their tectonic interpretation is included as a guide to the tectonic map in the associated web application. The mosaic of continental fragments and their relationships are those proposed by Ross et al. (1994a) and Ross (2002) with the domain outlines corrected by Pilkington et al. (2000).

The Precambrian lithosphere of western Canada was assembled into Laurentia (the present crustal configuration) between ca. 2.0 and 1.78 Ga (Hoffman, 1988, 1989; Ross et al., 1995; Ross, 2002). The tectonic components of the collisional events that assembled Laurentia consist of the pre-existing Archean and Proterozoic crustal material, and orogenic belts that welded them. The precollisional crust of the Alberta basement consists of a) Archean blocks that were affected by Proterozoic thermal and/or structural effects only along the edges (e.g., Medicine Hat block), and b) Archean crustal regions that have undergone vigorous Proterozoic reworking such that their Archean history is preserved only locally in the isotope record (e.g., Taltson magmatic zone). Proterozoic orogenic belts, which represent collision zones or welds between formerly disparate fragments of Archean and older Proterozoic crust, formed during the amalgamation of the Canadian Shield. These belts may include imbricate passive-margin and foreland sedimentary prisms and accreted arc and intraoceanic crust, and they underwent extensive magmatism generated during subduction and collision (Hoffman, 1988). The collisional belts involved the closure of oceanic basins and consumption of oceanic lithosphere that produced precollisional, subduction-related magmatic arcs dominated by calcalkaline magmatic rocks, which are commonly characterized by positive aeromagnetic signatures. The distinctive aeromagnetic signature of these plate-edge magmatic arcs is due to the presence of magnetite (Henderson et al., 1990; Thériault, 1992) and can be confidently traced from the exposed Canadian Shield to beneath the WCSB, despite the damping effect of the sedimentary cover on high-frequency aeromagnetic components (e.g., Taltson magmatic zone). Outlining and interpreting magnetic domains are more tentative where no outcrop control is available (Rimbey, Buffalo Head, and Vulcan domains).

The geophysical fabric of crustal components in the Alberta basement is truncated by three transverse structural elements (Figure 1), which have played an important role in Proterozoic tectonic assembly and younger tectonic evolution of western Canada: 1) the Great Slave Lake shear zone (GSLSZ) in the northwestern corner of the province, and associated younger faults of the McDonald–Hay River fault 'system'; 2) the Snowbird tectonic zone (STZ); and 3) the Vulcan structure (VS). The GSLSZ, the STZ, and the VS are used here as a framework to briefly describe the domains of the Alberta basement and their tectonic interpretation. These transverse structures are also important as they appear to have contributed to partitioning the subsidence and sedimentary processes adjacent to the Cordilleran margin (Cecile et al., 1997; McCartney, 2012).

The base of the crust is marked by the subhorizontal or smoothly undulating Mohorovičić discontinuity (Moho). The Moho is recognized widely on reflection seismic profiles as the generally abrupt transition from seismically reflective crust to nonreflective upper mantle at roughly 37–42 km depth. The publicly available seismic profiles in Alberta depict both gradational (within 5 km near Medicine Hat, SALT transect [e.g., Lamieux et al., 2000]) and sharp (within 1–2 km in central Alberta, PRAISE transect [Ross et al., 2000]) Moho transitions. The subhorizontal Moho is remarkably consistent in depth on the PRAISE transect and shows significant relief (up to 15 km vertical offsets) in parts of central Alberta. The 1992 CAT transect depicted a 10 km offset at the margin of the Thorsby magnetic domain and an increase of Hearne Province crust thickness of 33 to 42 km from west to east (Ross, 2002). The SALT transect depicts an irregular surface beneath the Medicine Hat block whereas ultradeep reflection sections show no clear Moho and instead depict subhorizontal reflectors to depths of more than 60 km (Ross, 2002; Ross and Eaton, 2002). Existing deep seismic data did not detect convincing upper mantle reflections as might be expected from tectonic scenarios of Proterozoic plate subduction.

The lithospheric mantle beneath Alberta has been investigated by magnetotelluric (MT) studies and various regional or more local mantle characteristics have been discussed in relation to known or inferred tectonic features of the overlaying crust (e.g., Boerner et al., 2000; Wu et al., 2002; Eaton et al., 2004; Turkoglu et al., 2009; Nieuwenhuis et al., 2014; Yin et al., 2014; Liddell et al., 2016).

5.1.1 Northern Alberta

The Great Slave Lake shear zone (GSLSZ) is an approximately 25 km wide zone of mylonitic rocks traced in outcrop for over 200 km along strike. It stretches along the southern shore of Great Slave Lake in the Northwest Territories (N.W.T.) into northwestern Alberta (Reinhardt, 1969; Hanmer, 1988; Hanmer et al., 1992). Granulite- to greenschist-facies mylonitic rocks and coplanar–cospatial cataclasites indicate syntectonic progressive unroofing of a crustal-scale long-lived shear zone. Although the GSLSZ has a strong magnetic signature, it is not associated with a gravity gradient, thus reflecting the similarity in density and thickness between rocks on either side of this discontinuity. Its magnetic signature continues to the southwest under the sedimentary cover of the WCSB to the foothills of the Cordillera (Hoffman, 1988, 1989). Broadband magnetotelluric (MT) data imaged the shear zone as a crustal-scale high-resistivity zone, 20 km wide, to a depth of 50 km and spatially correlated with an aeromagnetic low (Wu et al., 2002; Yin et al., 2014). Gravity and teleseismic studies in the same area indicate significant anomalies that affect the crust, Moho, and upper mantle (Hope and Eaton, 2002; Eaton and Hope, 2003; Eaton et al., 2004).

The GSLSZ is a major transcurrent shear zone that accommodated approximately 700 km of dextral slip during oblique collision between the Archean Slave and Rae provinces, followed by indentation of the Slave Province into the western Rae Province, and the buildup of the Thelon–Taltson Orogen (Gibb, 1978; Hoffman, 1987; Hanmer, 1988). During this process, slices of early Proterozoic precollisional crust in northern Alberta (the 2.4–2.1 Ga Buffalo Head and Chinchaga domains, see below) were pushed to the northeast, colliding with, and accreting to the western Rae Province (Ross, 1990; Ross and Eaton, 2002). Following the Slave Province–Rae Province collision, a crustal wedge south of GSLSZ (northern Alberta terranes including the western portion of the Taltson magmatic zone) escaped south from the eastern face of the Slave Province during its indentation (Hoffman, 1987; Hanmer et al., 1992).

Ductile deformation between 1986 and 1920 Ma was followed by a distinct episode of brittle deformation focused along the McDonald Fault (ca. 1735 Ma) in the N.W.T. (Henderson et al., 1990) and its subsurface continuation into Alberta, the Hay River fault zone (ca. 1722 Ma; Plint and Ross, 1993), during progressive unroofing and exhumation of a crustal-scale shear zone (Hanmer, 1988).

Northwest of the GSLSZ, the Alberta basement consists of the southern termination of two extensive domains of the Wopmay Orogen: the 1.95–1.91 Ga Hottah terrane (Hoffman and Bowring, 1984; Hildebrand et al., 1987) or magmatic arc (Ross, 2002) above a west-dipping subduction zone; and the 1.85–1.84 Ga Great Bear magmatic arc over an east-dipping subduction zone (Ross, 2002). The Wopmay Orogen represents accretion of Proterozoic crust along the western flank of the Archean Slave Province. The Pb and Nd isotopic signatures of the Great Bear magmatic arc are indicative of juvenile Proterozoic crust and mantle (Hildebrand et al., 1987; Bowring and Podosek, 1989; Housh et al., 1989; Gandhi et al., 2001), which is distinct from the predominantly Archean Nd signature to the south (Thériault and Ross, 1991). The Proterozoic crust has no southern counterpart, which could indicate that this Proterozoic orogen/arc terminated southward against a transform plate margin (Ross, 2002).

South of the GSLSZ, crustal domains of northern Alberta are tectonically attenuated (based on geophysical data) within the GSLSZ to the north and are truncated to the south along the STZ (Figure 1). In northeastern Alberta, the 1.98–1.92 Ga Taltson magmatic zone (TMZ) is the southern segment of the Thelon–Taltson Orogen, a 2250 km suture that marks the site of accretion of pre-2.0 Ga crust along the western margin of the Rae Province (Hoffman, 1988). Oceanic lithosphere was consumed beneath the western edge of Rae Province prior to and during these collision events, giving rise to a linear belt of syntectonic calcalkaline (I-type) plutons that evolved into peraluminous (S-type) plutons (Thériault, 1992). The TMZ is exposed on the Alberta portion of the Canadian Shield and in the Marguerite River watershed (Pană, 2010a; Powell et al., 2018). To the south in the subsurface of the WCSB, the TMZ continues for about 300 km as a north-trending, 150–200 km wide belt of strike-parallel, tightly corrugated, positive aeromagnetic anomalies, which are contained within broader aeromagnetic lows (Thériault and Ross, 1991). East of this belt, the basement was initially assigned to the Rae Province (Hoffman, 1987) and later to the Buffalo Head and Chinchaga crustal slices (e.g., Ross et al., 1994). Subsequent dating of core from the sub-Athabasca basement and from the Marguerite River basement have shown that the TMZ extends east beyond the Alberta boundary into Saskatchewan (Stern et al., 2003; Powell et al., 2018). Several north-trending 1980–1926 Ma strike-slip shear zones are exposed in the Alberta portion of the TMZ (Pană, 2010a, b). The most important were originally named, from west to east, the Warren and Allan shear zones (e.g., Godfrey, 1958, 1986; Langenberg, 1983). Subsequently, these shear zones have been assigned geographic names (e.g., Leland Lakes shear zone and Charles Lake shear zone, respectively; McDonough et al., 2000) in compliance with the recommendation of the International Stratigraphic Guide (Salvador, 1994) and consistent with the North American Commission on Stratigraphic Nomenclature (2005). Details regarding the extent and evolution of these regional shear zones can be found in McDonough et al. (2000), Pană et al. (2001), and Pană (2010a, b). These major shear zones are interpreted to have partly accommodated the southward escape of a crustal wedge during the Paleoproterozoic Slave Province indentation into the Rae Province (e.g., Hoffman, 1987, 1988). The southernmost exposures of these mylonite belts bend southwestward under the Devonian carbonate successions of the WCSB (Pană, 2010a) and terminate at, or possibly merge with, the Snowbird tectonic zone at the south end of the TMZ. Major dextral Black Bay and Grease River shear zones mapped in northern Saskatchewan, project east-southeastward into northeastern Alberta under the Athabasca Basin and possibly WCSB.

North-central Alberta is underlain by the Buffalo Head and Chinchaga domains (Figure 1), which continue into the adjacent N.W.T., comprising precollisional Proterozoic crust (2.34–1.99 Ga) flanked by coeval plutonic belts (Ross, 1990; Bostock et al., 1991; Ross et al., 1991; Villeneuve et al., 1993; McNicoll et al., 2000; Berman et al., 2013). To the west, the 1.98–1.90 Ga Ksituan domain is interpreted as a magmatic arc above a west-dipping subduction zone. To the east, the 1.98–1.92 Ga TMZ is a magmatic arc above an east-dipping subduction zone. The timing of imbrication of the Buffalo Head and

Ksituan domains is younger than 1900 Ma, which corresponds to the age of titanite formed during cooling of the Ksituan arc (Villeneuve et al., 1993), or slightly younger than the age of ductile strain observed in the GSLSZ (1920 Ma; Hanmer et al., 1992) and the TMZ (1926 Ma; McDonough et al., 2000). The subduction polarity was inferred based on the age of plutonic rocks on the supposed upper plate. However, in the Peace River Arch area, the collisional fabric depicted by the PRAISE reflection survey dips in the opposite (eastward) sense (Ross, 2002).

The central region of the Chinchaga and Buffalo Head terranes includes the Red Earth granulite domain, a subcircular area of deep crust, which indicates the supracrustal rocks of the basement have been deeply eroded (Burwash et al., 2000). Along the southwestern margin of the Buffalo Head terrane, the Kimiwan isotopic anomaly is a 250 by 50 km linear zone of crustal extension and basement metasomatism produced by meteoric fluids (retrogression and lowered $\delta^{18}O$ values in the 1 to 5‰ standard mean ocean water [SMOW] range; Burwash et al., 2000), possibly related to a strike-slip fault (Ross and Eaton, 2002). The Chinchaga and Buffalo Head terranes yielded ages, patterns of inheritance, and Nd signatures similar to the Taltson basement complex (within the TMZ), which is part of the Archean Rae Province (Thériault and Ross, 1991; McNicoll et al., 2000). This suggests that terranes of north-central Alberta may have been part of a coherent Proterozoic belt developed along the western margin of the Archean Rae Province (Thériault and Ross, 1991; Berman and Bostock, 1997; McNicoll et al., 2000).

West of the Ksituan domain is the Nova domain, a narrow slice of Archean (Slave) crust, which is associated with 1990 Ma metavolcanic–metasedimentary rocks (Villeneuve et al., 1993), appears to be stretched along the southern side of the dextral GSLSZ. The Nova domain is bound to the southeast by a narrow (1–3 km wide) aeromagnetic low interpreted as a fault juxtaposing the Nova and Ksituan domains.

Alternative interpretations have assigned the entire northern Alberta basement south of the GSLSZ to the Taltson domain (Hoffman, 1988) or to the Athabasca polymetamorphic terrane (Burwash et al., 1993, 2000).

5.1.2 Central and Southern Alberta Basement

The Snowbird tectonic zone (STZ) passes through central Alberta and is marked by the northeast-trending Thorsby magnetic low and a collinear gravity anomaly (Hope and Eaton, 2002). The continental-scale STZ is defined by a series of pronounced linear geophysical anomalies (gravity and magnetic) that extend from Hudson Bay to the foothills of the Canadian Cordillera (Hoffman, 1988). The STZ separates the Rae and Hearne provinces of the Canadian Shield and has been interpreted either as an intracontinental transform of Paleoproterozoic (Lewry and Sibbald, 1980; Lewry and Collerson, 1990) or Archean age (Hanmer et al., 1995), or as a Paleoproterozoic suture zone (Hoffman, 1989).

Seismic sections of the Central Alberta Transect (CAT) depict southeast-dipping crustal-scale reflections across the Hearne Province (including the Lacombe and Rimbey domains) interpreted to define a zone of crustal-scale imbrication with a northwest sense of vergence. Dipping reflectivity in the upper mantle along the northwest margin of the Hearne Province, a velocity anomaly in the middle to upper crust interpreted as serpentinite (oceanic crust?; Eaton and Cassidy, 1996), and the Rimbey belt of granites parallel to the edge of the Hearne Province are considered evidence for southeast-directed subduction (Ross, 2002).

An opposite (east) sense of vergence observed in seismic sections of the Trans-Hudson Orogen (Hajnal et al., 1996, 2005) suggests two coeval zones of Proterozoic underthrusting, which dipped towards each other resulting in substantial mantle modification beneath the Hearne Province, and coeval crustal-scale deformation and widespread magmatism 1820–1800 Ma throughout the Hearne Province (Ellis et al., 1998; Ross et al., 2000; Annesley et al., 2005)

Ross et al. (2000) suggested that the Charles Lake shear zone and the Leland Lakes shear zone of the TMZ were linked kinematically to a strike-slip basin or a zone of extension at their southern termination along the STZ (‘Thorsby basin’). Coeval counter-clockwise rotation and eastward translation of the Hearne Province (ca. 1.9 Ga) during plate consumption in the adjacent Trans-Hudson Orogen (Lewry et al., 1981; Lewry and Collerson, 1990) would have contributed to the opening of the hypothetical Thorsby basin, whereas the subsequent reactivation of the Hearne Province as the high-grade hinterland to the Trans-Hudson Orogen (ca. 1.8 Ga) led to the closing of the basin.

The Rimbey domain to the southeast of the STZ is a positive aeromagnetic anomaly interpreted as a 1.85–1.78 Ga magmatic arc dominated by biotite granites. This feature is also known as the central Alberta intrusions that parallel the STZ (Burwash et al., 2000). These granitoids show a predominantly crustal signature and were interpreted to be near-trench magmatic arc rocks that developed as the Thorsby basin closed and triggered melting of the accretionary wedge and near-trench crust (Lytwyn et al., 2000; Bouzidi et al., 2002).

The Lacombe domain consists of low-grade metavolcanic and metasedimentary rocks younger than ca. 2.3 Ga (possibly deposited in a back-arc basin of the Rimbey magmatic arc), whereas the Loverna and Eyehill domains are two subdivisions of the Archean Hearne Province (Villeneuve et al., 1993).

5.1.2.1 Vulcan Domain

The Vulcan domain is characterized by a pair of east-trending anomalies in both the gravity and magnetic fields that separate predominantly northeast-trending anomalies of the Hearne Province (Loverna block) to the north, from northwest-trending anomalies of the Medicine Hat block to the south (Thomas et al., 1987; Eaton et al., 1999). Over time this peculiar magnetic low received different tectonic interpretations (see below) and became known as the Vulcan structure (VS). The eastern portion of the distinctive VS aeromagnetic trend curves and merges into anomalies of the internal zone of the Trans-Hudson Orogen, hence a Proterozoic age for the VS. The orientation of seismic reflections on either side of the VS are dramatically different providing further evidence that the VS is a major structural boundary; specifically, they strike northeast and dip southeast in the Loverna block (Hearne Province) to the north, whereas they strike northwest and dip southwest in the Medicine Hat block to the south (Lemieux et al., 2000). The VS was originally interpreted as a Precambrian rift (Kanasewich et al., 1969) but, based on subsequent LITHOPROBE data, the VS was interpreted as a Proterozoic (ca. 1.8 Ga) collisional boundary (a suture zone) between the Medicine Hat and Loverna (Hearne Province) blocks, with no evidence for younger rifting (Eaton et al., 1999). Although the VS lacks features comparable to exposed Precambrian orogens, it has been interpreted as a suture zone because it separates contrasting Archean crustal blocks (Eaton et al., 1999).

Potential-field modelling and interpretation of reflection data may indicate a midcrustal intrusive body, which would be consistent with the interpretation of the VS as a site of consumption of oceanic lithosphere (Eaton et al., 1999). Note, however, that the VS lacks an apparent collinear syntectonic magmatic belt as might be expected along a suture that involved subduction of oceanic lithosphere and that the Medicine Hat block was relatively unaffected by the Proterozoic assembly processes (Boerner et al., 1997, 2000). Ross (2002) recognized the inconsistency and suggested that the flanking basin must have been relatively small such that slab-related melting was never a significant part of the suture process. Alternatively, the VS may represent a broad region of Proterozoic intracontinental deformation.

The VS forms the northern structural boundary of the Medicine Hat block (MHB), which preserves a predominantly Archean geological history. The MHB is composed of northwest-trending belts of Archean gneisses and plutonic rocks that range from 2.7–2.6 Ga and a single occurrence of Alberta's oldest rock, a 3.3 Ga diorite gneiss (Villeneuve et al., 1993). A detailed discussion of the inferred structure and evolution of the MHB can be found in Lemieux et al. (2000). To the south in the northern United States, the aeromagnetic fabric of the Medicine Hat block is truncated or overprinted by the northeast-trending potential-field anomalies that define the Great Falls tectonic zone, a major Proterozoic (>1.8 Ga) structural discontinuity, which separates the MHB from the Archean Wyoming craton (Thomas et al., 1987; Lemieux et al., 2000).

5.2 Inferred Postcollisional Mafic Sheets in the Alberta Basement

Basement fabrics, depicted by reflection seismic, are inferred to have been acquired during Proterozoic collision. In the upper crust of the Peace River Arch of west-central Alberta and in the lower crust of southern Alberta, subhorizontal high-velocity features appear to crosscut the Proterozoic collision fabric and were interpreted as individual mafic intrusive bodies (e.g., Ross and Eaton, 1997; Lemieux et al., 2000). The emplacement of melts as sheets indicates a laterally compressive stress field in that the least compressive stress was vertical and not horizontal as in the case of dike emplacement.

In the central and eastern Peace River Arch area, the Winagami reflection sequence identified within the upper 15 km of the Precambrian crust in the PRAISE reflection data was interpreted as intrusive mafic sheets with thicknesses of 80–120 m (Ross and Eaton, 1997). In southern Alberta, within the Archean Medicine Hat block, the SALT transects and various other seismic studies depicted subhorizontal reflections in the lower crust and upper mantle, which have been interpreted as sills (Lemieux et al., 2000). They form a 10–25 km thick layer of lower crust, with an anomalous velocity (>7.0 km/s), that extends southwards into the United States, through the Great Falls tectonic zone into the Wyoming craton. Cenozoic magmas of the Montana Alkalic Province include ca. 1825–1700 Ma mafic granulite xenoliths (Davis et al., 1995). This lower crustal material may also be the result of Proterozoic underplating.

Proterozoic mafic sheets may locally modify crustal strength and impart anomalous elastic behaviour of the crust and transmission of stress.

6 Western Canada Sedimentary Basin

6.1 Phanerozoic Tectonic Evolution of the Western Canada Sedimentary Basin

The strata of the WCSB were deposited in three different general tectonic settings: a passive continental margin from the Neoproterozoic to Middle Devonian, a back-arc setting from the Late Devonian to Jurassic, and a foreland basin between the Jurassic and Eocene (e.g., Monger, 2014). Evidence for the Late Devonian–early Carboniferous Antler orogeny (e.g., Stevenson et al., 2000; Root, 2001) is limited and somewhat controversial at this latitude in the Cordillera (Pană, 2006; Hauck et al., 2017a). However, multiple Famennian and Tournaisian unconformities (Johnston and Chatterton, 2001), Sm-Nd systematics of local Devonian–Carboniferous clastic deposits in the Jasper area (Hauk et al., 2017a), and isolated intrusive rocks in the adjacent Canadian Cordillera (Pană and Smith, 2021) may be related to Antler-age tectonism at the latitude of present-day Alberta. Therefore, it is not precluded that far-field stresses associated with the Antler tectonism triggered lithospheric flexure accompanied by faulting of the Paleozoic stratigraphy in southern Alberta.

Far-field stress related to the purported Late Devonian–early Carboniferous Antler orogeny and the Jurassic to early Eocene Cordilleran contraction to the west may be responsible for faulting in the Alberta Basin. The west-dipping normal faults depicted by the Southern Alberta Transect (SALT) indicate Precambrian basement faults that can be traced upwards through the Campanian Belly River Group. Thus, the basement had been reactivated—most likely during the foreland stage of the basin's evolution—and constitutes undisputed evidence for downflexing of the North American craton during the well-documented Cordilleran tectonic loading (Pană and van der Pluijm, 2015; Pană et al., 2018a, b).

Postorogenic isostatic re-equilibration of the Cordilleran foreland system was accompanied by the removal of up to 2 km of strata near the orogen (foothills) and approximately 500 m to the east in the Alberta Plains, and a minimum of approximately 150 m in the Cypress Hills (Nurkowski, 1984; Kalkreuth and McMechan, 1988, 1996), which may have triggered minor late Cenozoic faulting or fault reactivation.

The bedrock in the Alberta Plains is covered by Neogene fluvial deposits, Quaternary glaciogenic materials, and postglacial sediments of highly varied thickness and distribution (modelled values ranging from less than 1 m to as much as 360 m; Atkinson et al., 2020).

6.2 Phanerozoic Basement Arches and Crustal Reactivation

The general mechanisms at the origin of cratonic arches and crustal reactivation that have influenced the accumulation of Phanerozoic sediment in the WCSB (Eaton et al., 1999; Ross, 2002) include

- the distal effects associated with thermally driven subsidence and flexure in a passive craton margin adjacent to the Cordillera; and
- tectonic loading in a foreland setting when the margin became contractional (Bond and Kominz, 1984; Beaumont et al., 1993), coupled with deep mantle flow during subduction events in the Cordillera that may have triggered basin subsidence (Pysklywec and Mitrovica, 2000).

The thick cover of Cambrian to Cenozoic sedimentary rocks of the WCSB has been used to assess the degree to which crustal and (or) mantle lithosphere has controlled the pattern and magnitude of vertical motions in western Canada over the last 500 million years. Patterns of sediment accumulation contained within the sedimentary record are the effects of lithospheric structures and processes (Bond and Kominz, 1984; Beaumont et al., 1993) and have been assessed through integration of lithospheric-scale geophysical techniques with the sedimentary record (Eaton et al., 1995; Hope et al., 1999; Ross and Eaton, 1999). Three low-relief, basement-cored, cratonic arches are known in the Alberta portion of the WCSB: the Peace River Arch in northwestern Alberta and northeastern British Columbia, and the 'Montania' promontory and Bow Island Arch (Sweetgrass Arch) in southern Alberta. The Peace River Arch and Montania spatially coincide with regions of Proterozoic mafic magmatism in the basement. The presence of large quantities of mafic material may have produced differences in mechanical strength of the crust, and thus influenced the responses to stress in those regions (Ross, 2002).

6.2.1 Tathlina Arch

At the north end of the Alberta Basin, the Liard Basin is a dramatic feature in northeastern British Columbia and the N.W.T., bounded to the east by the Bovie Lake fault-and-fold complex. The easterly trending Tathlina Arch can be defined from isopachs of the Middle Devonian Elk Point Group. Although the well control is sparse, north of the Alberta border the lower Elk Point Group isopach map suggests an east-west ridge that curves south in the northwestern corner of Alberta (Okulitch, 2006a, b).

6.2.2 The Peace River Arch

The Peace River Arch (PRA) region trends to the east-northeast and represents at least 500 million years of anomalous uplift and subsidence in the northern part of the Alberta Basin, which included an early phase of positive relief above the sea floor during the Neoproterozoic through the Devonian followed by two phases of inversion and enhanced subsidence in the Late Devonian through the Cretaceous (O'Connell et al., 1990; O'Connell, 1994). It is an entirely subsurface structure, characterized by many sedimentological, structural, and diagenetic aberrations (deMille, 1958; Lavoie, 1958; Williams, 1958; Sikabonyi and Rodgers, 1959; Stott, 1982; Cant, 1988). The PRA developed nearly perpendicular to the northerly trending, curvilinear basement terranes, as inferred from aeromagnetic-anomaly patterns and horizontal gravity-gradient maps that show a slight thinning of the crust close to the axis of the arch. This thinning was interpreted to indicate a passive flexural isostatic mechanism for PRA formation (Ross, 1990).

The PRA does not appear to bear any spatial relationship to basement domains, although some Carboniferous faults may have inherited shallow basement structure (Ross, 1990; Eaton et al., 1999; Ross and Eaton, 1999). For example, the Carboniferous Dunvegan Fault coincides with a segment of the aeromagnetic 'break' between the Precambrian Ksituan and Chinchaga domains. The collapse of the basement arch and the development of the Carboniferous Peace River Embayment (PRE) were implicitly related to normal faults and graben structures (e.g., Cant, 1988). A number of basement faults documented in published geological reports over the last half century in the PRA region have identified vertical offsets of several hundred metres (Pană et al., 2001).

6.2.3 Montania

The Medicine Hat block of southern Alberta is part of the larger paleogeographic feature recognized in the Cordillera as the Montania promontory (e.g., McMechan and Price, 1982). The promontory extends through northern Montana, southeastern British Columbia, and southern Alberta (Deiss, 1941; Norris and Price, 1966; Ross, 1995; Norris, 2001). Montania appears to have been topographically high at a number of periods during sedimentation of the Mesoproterozoic Belt-Purcell Supergroup (ca. 1.45 Ga; Hoy, 1993; Ross and Villeneuve, 2003; Pană et al., 2018c), Neoproterozoic Windermere Supergroup (750–600 Ma; Lis and Price, 1976), and the lower Paleozoic sequence (Cambro-Ordovician; Norris and Price, 1966). This feature is loosely defined in literature; hence, no axis has been traced in Figure 1.

6.2.4 Bow Island Arch

The Bow Island Arch is the northeasterly trending extension, into Alberta, of the structurally distinct and more complex Sweetgrass Arch of Montana. The Sweetgrass Arch hosts Eocene intrusives, which also extend into southern Alberta, and consists of a North Arch (the Kevin-Sunburst Dome), which straddles the Montana–Alberta border, and a South Arch. The North and South arches are separated by the possibly dextral, northeast-trending Pendroy Fault.

The Bow Island Arch, defined by the 1000 m contour of the foreland basin–fill isopach, is a subtle, mildly positive, broad, structural element in the central and eastern Medicine Hat block (Figure 1), periodically separating the Alberta and Williston basins in southeastern Alberta (Kent and Christopher, 1994). Isopachs and structural contours of the Devonian system in southern Alberta suggest an arch trending southwesterly towards the western edge of the WCSB (Kent, 1987), which may have been contiguous with the antecedent Proterozoic to early Paleozoic Montania (Wright et al., 1994).

The Sweetgrass Arch was active during several stages, starting in the late Paleozoic and becoming more clearly defined during the Mesozoic (best expressed during the pre-Devonian and the pre-Jurassic [Herbaly, 1974]) and Cenozoic (e.g., Williams and Burk, 1964; Kent, 1987).

6.2.5 Reactivation of the Sub-WCSB Basement

The crystalline basement forms the floor to the long-lived WCSB. Basement reactivation is of critical importance in understanding the role of basement structure in the Alberta Basin's evolution, particularly for controlling sedimentation and diagenetic patterns in the basin. In the AGS's web application, one can observe that some faults in the Phanerozoic rocks of northern Alberta coincide with structures in the crystalline basement, such as the GSLSZ, shear zones in the TMZ, and the Peace River Arch (see discussion in Pană et al., 2001). It remains, however, unclear whether or not there was persistent and through-going control of sedimentation patterns by antecedent basement structure (Ross and Eaton, 1999, 2001; Gay, 2001).

In general, there is widespread acceptance of basement reactivation in the Alberta Basin as an explanation for anomalous linear sedimentation patterns inferred to have been controlled (or at least influenced) by basement structures. In principle, the concept is justified by the observation that the Great Slave Lake, Leland Lakes and Charles Lake shear zones include low-grade phyllosilicate minerals and even cataclasites that are not annealed, and have certainly evolved through strain softening and reaction weakening to become weaker than adjacent rocks and therefore are a focus of younger deformation (White and Knipe, 1978; Wintsch et al., 1995). This leads to the development of a fault plane or fault zone that is collinear with the ductile shear zone, but with substantially diminished rock strength, largely through the production of phyllosilicate zones (Hanmer, 1988).

Ross and Eaton (1999, 2001) noted that the basement reactivation concept, embraced indiscriminately, led to the proliferation of the preconceived idea that basement structures throughout the basin are inherently zones of weakness. It has been long established that deformation below the brittle-ductile transition zone in the crust (12–15 km depth) results in ductile mylonite, which may become stronger than adjacent rocks (e.g., Sibson, 1977; White et al., 1980). Such processes are usually invoked to explain branching and lateral spreading of shear zones over several kilometres in width, as deformation shifted into weaker rocks adjacent to strain-hardening regions of the shear zones (Hanmer, 1988). Ross and Eaton (1999) argued that "direct basement control of the presence and orientation of faults in the sedimentary section seems unlikely," as the strength and thermal age of sub-WCSB lithospheric mantle was too great to allow pervasive basement reactivation. Ross and Eaton (2001) integrated cross-sectional (seismic) data with map (aeromagnetic) data acquired over regions of previously inferred basement reactivation (e.g., the southern PRA), and suggested that "although evidence of basement reactivation is present locally in the Alberta Basin, its correlation with basement structural fabrics is not pervasive", rather, the correlation is limited or very subtle.

Nonetheless, new structures can and do form in the Alberta Basin, they crosscut the subhorizontal near-basement seismic reflectors and their orientation is oblique to pre-existing structural fabrics. Whether basement faults are reactivated or are new depends on the rheology of the basement and on the orientation and rheology of pre-existing fault zones. The strike and dip of basement fractures relative to paleostress axes should be carefully considered before postulating structural reactivation. The degree of reactivation is spatially variable and decays with distance from the Cordillera, suggesting lithosphere-scale thermomechanical control (Ross and Eaton, 2001). Also, it has been demonstrated that reactivation of basement faults during extension is mechanically more likely than during compression (Sibson, 1995). Reactivation of the basement has often been invoked as a default mechanism to explain local coincidence of trends of isopachs, facies transitions, extent of erosion on transgressive erosional surfaces, synsedimentary faults, and modern hydrocarbon production trends with basement structures (Gay, 2001 and references therein). Precambrian fault reactivation is viewed as the principal mechanism responsible for localizing particular facies or thickness changes, as seen in Devonian reefs (e.g., Greggs and Greggs, 1989), drainage patterns in the Devonian (e.g., Dec et al., 1996) or Cretaceous (e.g., Leckie et al., 1990), depositional patterns inferred from stratigraphic thickness changes (e.g., Hart and Plint, 1990), or Triassic facies changes (e.g., Dix, 1990). The linear distribution of some oil, gas, and coal deposits in the Alberta Basin, in a regional and/or local sense, is believed to be caused by reactivation of high-angle basement faults (Lyatsky, 2000; Lyatsky and Pană, 2003). The close correlations of the long axes of oil fields in the Alberta Basin with one of the main jointing directions observed in the bedrock (Babcock, 1974, 1975), and with lineament directions (derived from imagery interpretation; Misra, 1991) are considered additional evidence of basement control at small and large scales, respectively (Gay, 2001). It must be emphasized that both lineament analysis on satellite imagery and isopach patterns derived from well data are only means of inference or speculation on the existence of a basement fault. Basement faults are not 'mapped' from the surface or from the sedimentary section! In particular, the joints measured by Babcock (1975) and Pană (2002) in northeastern Alberta are in Phanerozoic rocks and may or may not have an explicit connection with the Precambrian basement.

Ideally, mapping of tectonic discontinuities in the sub-WCSB basement would require a combination of geological data, airborne geophysical data, and seismic images of both the sedimentary section and the underlying basement. Faults known and inferred in the stratigraphic sequence are usually compared and matched with basement 'breaks' shown by the aeromagnetic data, either as first vertical derivative or profile residual maps. Their 'commonality' (Leblanc and Morris, 1999) in some areas led to the supposition that basement control of Phanerozoic structures in the Alberta Basin is quite common, if not pervasive (e.g., Gay, 2001).

6.2.6 McDonald Fault Zone

Between the Peace River Arch and the Tathlina Arch is the northeast-trending Hay River Fault and coincident GSLSZ (Figure 1), which has up to 700 km of dextral displacement in lower Proterozoic basement rocks. Vertical displacement and (possibly) horizontal offset are present in Phanerozoic strata near the Hay River Fault, but these are difficult to substantiate without geophysical data.

In northwestern Alberta, Barss et al. (1970) recognized a pervasive northeasterly fault pattern in the hydrocarbon-prospective Rainbow area and speculated that the McDonald fault zone was intermittently active during the Phanerozoic. A Pb-Zn mineralized breccia from the Middle Devonian Keg River Formation was reported from well 16-34-118-21W5 (Turner and McPhee, 1994), which is located above the magnetic expression of the GSLSZ. The only isotope age that is related to the tectonic activity of the GSLSZ in the unexposed Alberta basement is an $^{40}Ar/^{39}Ar$ age of 1780 Ma (Plint and Ross, 1993); therefore, the Keg River Formation breccia indicates Devonian or younger brittle reactivation, most likely as discrete faults overprinting the basement shear zone.

Although the drift thickness in the northwestern corner of Alberta is approximately 200 m, the drainage pattern is parallel to the inferred trend of the McDonald fault zone. Landsat data depict a zone of east-northeast-trending lineaments, 150 km wide in the west and narrowing eastward, which appears to be related to the McDonald fault zone (Misra et al., 1991). Based on an integration of these data with the linear hydrocarbon production trends, these authors suggest a strong correlation between basement features and oil and gas fields.

Other depositional changes possibly controlled by basement structures exist (e.g., Pană et al., 2001). For example, one very attractive theory is that tectonic discontinuities influenced the formation of a 400 km long, straight and narrow (5 km wide), northeasterly trending belt of dolomitized carbonate rocks in central Alberta, the enigmatic Rimbey-Leduc-Meadowbrook reef trend, however, there may be other possible interpretations.

6.3 Other Subregional and Local Structures in the Alberta Basin

Subregional and local structural features in the Alberta Plains include

- blind thrust faults east of the elusive Cordilleran deformation front,
- normal and strike-slip faults,
- compaction and drape structures over reefs or other competent rock bodies,
- polygonal dissection faults,
- salt and carbonate dissolution structures, and
- meteorite impact craters.

Several proven impact craters (Steen River, Eagle Butte, Whitecourt) and other inferred astroblemes (James River, Manyberries, Bow City) have been included in this structural compilation of the Alberta Basin. All astroblemes show a subcircular crater with raised circumferences cut by radial faults or fractures and some have a central uplift.

A variety of dissolution features are present in the basin, and karst topography is present on several erosional surfaces. Dissolution of Devonian upper Elk Point Group salt has occurred around reefs of similar age. The timing of dissolution varies and has been interpreted from seismic and subsurface well information. Dissolution of Devonian salt is also evident at the sub-Mesozoic unconformity controlling, to some extent, the variation in the thickness of overlying Cretaceous strata as well as the relief on post-Cretaceous surfaces in the eastern and northeastern WCSB.

Fracture-associated hydrothermal karst and dolomitization were noted in the vicinity of the Peace River Arch in west-central Alberta (Packard et al., 2001). Similarly, karst-related subcircular low elevation anomalies in the Exshaw Formation / Wabamun Group, recognized on the 3D reflection-seismic images in the vicinity of faults in southern Alberta, are underlain by localized dissolution of the Stettler

Formation anhydrite and by intervals of secondary dolomitization in the Stettler and Big Valley formations carbonate rocks; both appear to be related to fluid migration along faults (Galloway et al., 2018). In contrast to these localized karst dissolution features, regionally pervasive karsting and mass removal are related to basin-scale fluid flow. Salt removal in the Prairie Evaporite Formation in northeastern Alberta may also be related to regional fluid flow along faults (Hauck et al., 2017b).

Fault-associated dissolution, dolomitization, and collapse of uppermost Devonian strata (e.g., Mountjoy and Halim-Dihardja, 1991; Packard et al., 2001), and unconformities in the uppermost Wabamun Group and Exshaw Formation (Johnston et al., 2010) are considered far-field effects of the Devonian–Mississippian (Antler orogeny) tectonism in different parts of the WCSB.

Microseismicity induced by fluid injection into or extraction from strata of the WCSB show earthquake foci in the first few kilometres of the basement and suggest potential hydraulic conductivity to basement-rooted natural faults (Schultz et al., 2015a, b).

In terms of present-day structural features, adjustment along pre-existing fault planes is undoubtedly occurring and is expressed as geomorphological trends; lineaments on the Alberta Plains commonly reflect salt-solution trends and deep faults.

6.4 Intrusive Rocks in the WCSB

6.4.1 Kimberlite Pipes in Northern Alberta

Kimberlite pipes have been included in the structural compilation because their emplacement in the crust is inferred to have been controlled by reactivated major deep-seated structures that facilitated kimberlite melt transit through the lithosphere (e.g., Eccles et al., 2001; Kjarsgaard et al., 2017). The northern Alberta kimberlite province includes three separate Late Cretaceous kimberlite clusters or fields: the Mountain Lake cluster consists of two closely spaced pipes; the Buffalo Head Hills field has 38 pipes; and the Birch Mountains field hosts eight pipes (Eccles et al., 2003). These kimberlite clusters are located in the vicinity of the PRA (one near the southern margin and two roughly along its eastward projection) but not within the PRA *sensu stricto*. No definitive link with basement structure has been found. Although several structural-stratigraphic lineaments have been documented within a few kilometres of known kimberlite, no obvious structural pattern can yet be confidently related to known kimberlite fields (e.g., Pană et al., 2001).

6.4.1.1 Mountain Lake Cluster

The Mountain Lake pipes were discovered by Monopros Ltd. (then a Canadian exploration subsidiary of De Beers) in 1989–1990, northeast of Grande Prairie, Alberta. The area was initially targeted as a result of a positive stream-sediment heavy-mineral sample from Mountain Lake creek, which is located directly west of the pipes. The first kimberlitic rocks were unearthed by shovel, on what is now known as the Mountain Lake South pipe. The age of the Mountain Lake pipes (ca. 76–68 Ma) was estimated based on palynological and apatite fission track results (Leckie et al., 1997; Wood et al., 1998).

The Mountain Lake ultrabasic pipes appear to have been emplaced at the intersection of a Jurassic to Cretaceous zone of tectonic instability that is subparallel to the Cordilleran front, and a northeasterly fault zone bounding the pre-Carboniferous PRA (Pană et al., 2001).

6.4.1.2 Buffalo Head Hills Field

Along the east flank of the Buffalo Head Hills in the Red Earth Creek area, shallow high-frequency magnetic anomalies, coincident with reflection seismic disruptions, led to the identification of the first potential kimberlite diatreme(s). In 1997, Ashton Mining of Canada Inc. discovered the kimberlites on the southeast flank of the Buffalo Head Hills and by the end of 2003, 38 kimberlitic pipes had been located in this region. A large percentage of the pipes at the Buffalo Head Hills are diamondiferous, with at least six of the kimberlites containing estimated grades of >3 carats per hundred tonnes (cpht) and one pipe (kimberlite K252) having preliminary mini-bulk sample grades of 55 cpht. The U-Pb perovskite dating of kimberlites (K5, K7A, and K14) from the Buffalo Head Hills field yielded Coniacian ages between 86 ±3 and 88 ±5 Ma (Heaman et al., 2003; Skelton et al., 2003).

The Buffalo Head Hills kimberlite field appears spatially related to periclinal closure of the Devonian PRA. This corresponds to an elongated, roughly northerly trending zone of thickness and facies changes in the Devonian Woodbend Group strata, which may be structurally controlled (Eccles et al., 2001).

6.4.1.3 Birch Mountains Field

The Birch Mountains kimberlite field was initially discovered by the identification of subtle, but recognizable, localized, aeromagnetic anomalies from a fixed-wing aeromagnetic survey, which was then followed up by ground magnetic surveys. Between 1998 and 2000, eight pipes were discovered in the Birch Mountains. The U-Pb perovskite and Rb-Sr phlogopite dating indicate that the Birch Mountains kimberlites were emplaced between 70.3 ±1.6 and 77.6 ±0.8 Ma (Aravanis, 1999).

The Birch Mountains kimberlite field intersects the Rimbey-Leduc-Meadowbrook reef trend, both of which may be related to a subtle, seismically unresolved basement feature (Switzer et al., 1994). Furthermore, in this area, faults can be inferred from several Devonian lineaments that demarcate facies changes within the Woodbend basin, and from several Cretaceous lineaments suggested by isopach maps of the Viking Formation and Mannville Group strata.

6.4.2 Potassic Dikes in Southern Alberta

The exposed mafic alkaline dikes in southern Alberta and circular intrusions in the Sweetgrass Hills of northern Montana range in age from ca. 54 to 50 Ma (Baadsgaard et al., 1961; Currie, 1976; Hearn et al., 1978; Marvin et al., 1980). Davis and Kjarsgaard (1994) obtained a Rb-Sr isochron date of 50.3 ±0.5 Ma for an olivine minette dike and Buhlmann et al. (2000) reported Rb-Sr isochron dates of 49.0 ±0.8 and 52.0 ±1.7 Ma for mica clinopyroxenite inclusions, and a Rb-Sr model date of 50.0 ±0.3 Ma for a late-stage minette dike. The intrusions occurred at a time of widespread extension and volcanism within the Cordillera, towards the end and immediately after the compressive deformation of the Omineca belt and the Rocky Mountain fold-and-thrust belt (e.g., Gervais et al., 2010; Pană and van der Pluijm, 2015; van Rooyen and Carr, 2016).

These Eocene magmatic rocks have received much attention due to their gold and diamond potential (Lau and Dudek, 1992; Dufresne et al., 1996). Kjarsgaard (1997) considered whole-rock and mineral geochemistry of the Milk River minettes to be consistent with possible magma derivation from the diamond-stability field in the mantle, but pointed out that the tectonothermal and metasomatic overprinting of the lithospheric mantle beneath the Archean Medicine Hat and Wyoming basement might have affected diamond preservation. Rukhlov and Pawlowicz (2012) reviewed previous petrological data and presented new geochemical and mineralogical data, and metallogenetic considerations for the Eocene potassic intrusions and related hydrothermal veins in southern Alberta.

High-resolution aeromagnetic data north of the exposed alkaline rocks of southern Alberta indicated two clusters of short-wavelength linear features: one trending northwesterly between the town of Milk River and city of Lethbridge; and the second trending north-northeast near the city of Medicine Hat (Ross et al., 1994b). The linear and subparallel disposition of these features suggested that they represent swarms of mafic dikes up to 30 km long, at depths of about 250 m in the sedimentary column, which may be correlative with mafic potassic dikes of Eocene age exposed in the Sweetgrass Hills (Ross et al., 1994b).

7 Surficial Lineaments

Aerial photographs and satellite image interpretation may represent the only means of structural mapping in the poorly exposed, highly vegetated terrains of Alberta. Although the Alberta Plains are blanketed by Pleistocene drift, the present-day drainage system appears to be, to a certain degree, structurally controlled. The explanation may be that preglacial river valleys preferentially occur along or within more recessive and/or tectonized rocks and were deepened by ice action during glaciation (Misra et al., 1991). As well, ice melting and recent fluvial erosion may have been concentrated along topographic lows inherited from preglacial time. However, a large number of glacial lineaments do not show any direct bedrock control and, consequently, discrimination of tectonic from glaciotectonic lineaments is essential when attempting to map faults in the Alberta subcrop.

Airphotos and satellite imagery were used to identify surficial lineaments believed to extend from the surface into the Precambrian basement and to have played a key role in the linear orientation of oil fields in the Alberta Plains. The possibilities and limitations of recognizing geologically significant lineaments by analysis of digital elevation models (DEM), airphotos, and RADARSAT imagery was discussed in Pană et al. (2001). Fusion of these data with aeromagnetic and gravity data will add the geophysical characteristics of the deep crust and upper mantle to form a more complete picture of Alberta geology.

From early lineament studies of airphotos (e.g., Blanchet, 1957; Sproule, 1968; Babcock, 1974, 1975; Ozoray, 1972) to a study that combined Landsat MSS (Multispectral Scanner), Thematic Mapper (TM), and Seasat satellite radar images (Misra et al., 1991), all such studies identified two dominant orthogonal sets of lineaments; one trending northeast and the other northwest. In general, these lineaments are believed to represent nearly vertical tensional stress faults in Phanerozoic strata. Misra et al. (1991) argues that the northwest lineament trend defines a southwest-facing arc (a forebulge-like feature), which is roughly parallel to the western edge of the Canadian Shield. Although both lineament trends commonly occur together, either of them may predominate in a particular region. Many lineaments are segments of much longer composite structures, some of which extend for several hundreds of kilometres. A few lineaments with the northwest and northeast trends typical of the WCSB appear on the adjacent Canadian Shield, close to the edge of the WCSB. Away from the basin margin, the simple orthogonal pattern is replaced by a complex of short, intersecting lineaments, which characterizes the rocks of the Canadian Shield.

The partial overlapping and density increase of surficial lineaments with basement structures supports both the idea of basement reactivation and of a genetic relationship between surficial lineaments and bedrock/basement structures. Good examples are in the Peace River Arch area and along the Hay River Fault/GSLSZ (Misra et al., 1991; Pană et al., 2001).

In addition to many lineaments compiled from aerial and satellite imagery studies, the present compilation includes lineaments traced by the first author of this report along straight river courses and near right-angle bends in rivers or other topographic features. Short topographic lineaments were mapped very conservatively for the present report, paying particular attention to the discrimination of tectonic from glaciotectonic lineaments. More aggressive mapping would definitely result in a much higher lineament density and longer lineaments.

In addition to the surficial lineaments that may be related to structural features in the bedrock and even in the crystalline basement as discussed above, the bedrock and overlying Quaternary sediments of the Alberta Plains were locally involved in glaciotectonic deformation at the margin of the Laurentide Ice Sheet (Moran et al., 1980; Phillips et al., 2017). Hill-hole pairs, small-scale push features, much larger composite ridges, and thrust-block moraines mark the former positions of ice marginal stillstands or readvances and can be observed at different locales in the Alberta Plains, such as Neutral Hills, Misty Hills, and Mud Buttes in east-central Alberta (Shetsen, 1990; Fenton et al., 2013; Atkinson et al., 2014, 2018b). The most spectacular and best studied locale is Mud Buttes, where spectacular folds and thrusts of sandstones, siltstones, and mudstones of the Cretaceous Belly River Group formed during the later stages of ice sheet recession from Alberta (Phillips et al., 2017).

Although the types of glaciotectonic structures are similar to those observed within orogenic fold-and-thrust belts and consequently the same nomenclature (folds, thrusts, stacked thrust sheets, basal décollement, polyphase deformation) is used, the glaciotectonic structures are not included in the present web application because they i) are not the result of endogenic (internal Earth) forces, ii) involve irregular rock and sediment masses, iii) developed at a much smaller scale over significantly shorter timescales (within tens to hundreds of years and even within a year), and iv) have already been included in other AGS products (e.g., Atkinson et al., 2014, 2018a, b).

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