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VOLCANOLOGY AND STRATIGRAPHY OF THE LUNDBERG ZONE, BUCHANS, NEWFOUNDLAND

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ABSTRACT

The Buchans Group of central Newfoundland is a structurally complex stratigraphic package that hosts stratigraphically controlled volcanic-hosted massive sulphide mineralization. Previous work has divided the Buchans Group into four formations based on the stratigraphy in the Lucky Strike area. Recent drilling through the Lundberg Zone provides an opportunity to test this stratigraphy. Logging of the Lundberg Zone identified an almost intact stratigraphy consisting of, from base to top: basaltic andesite pillow breccia, lower basaltic andesite, lower sedimentary sequence, upper basaltic andesite, rhyodacite, upper sedimentary sequence, and rhyolite. Logging of drillcore places the pillow breccia and lower basaltic andesite in the Lundberg Hill Formation, the upper basaltic andesite in the Ski Hill Formation, the upper sedimentary sequence and rhyodacite in the Buchans River Formation. The rhyolite unit does not form part of the stratigraphy and was structurally emplaced over the Buchan River Formation. Because of its unique characteristics, the rhyolite is placed in an informal 'Lucky Strike hanging-wall succession.' Stockwork mineralization is hosted by the upper Ski Hill Formation and parts of the Buchans River Formation, which also hosts exhalative and transported sulphides. In addition, massive sulphide clasts occur within sedimentary rocks in the upper basaltic andesite, indicating volcanic-hosted massive sulphide potential within the Ski Hill Formation. The entire sequence is continuous across the study area and is an excellent guide for stratigraphically controlled mineral exploration in the Buchans area.

INTRODUCTION

The complex structure and stratigraphy of the Buchans area had not been appreciated prior to the recognition of thrust faults (*e.g.*, *see* Thurlow and Swanson, 1981) and antiformal thrust stacking (*e.g.*, Calon and Green, 1987); later, the area has also been imaged using seismic reflection (*see* Figures 1 and 2; *e.g.*, Thurlow *et al.*, 1992). The recognition of thrust faults led to a thrust repetition model of the volcanic-arc stratigraphy (*e.g.*, Thurlow and Swanson, 1987). Following the termination of base-metal mining operations at Buchans in 1984, advances in lithogeochemistry have enabled testing of the stratigraphic correlations (Jenner, 2000). The geochemical database collected by Jenner (*op. cit.*) revealed several issues in the Buchans Group stratigraphy not consistent with previous correlations; however, the data were not detailed enough to fingerprint the various formations.

This study incorporates petrographic and geochemical data (van Hees, 2012), to examine the stratigraphic context of the stockwork (Lundberg Zone) peripheral to the largest volcanogenic massive sulphide (VMS) deposit in the Buchans mining camp of central Newfoundland (Lucky Strike deposit, Figure 2; Thurlow and Swanson, 1981, 1987; Thurlow *et al.*, 1992). In 2008, extensive drilling of the Lundberg Zone by Royal Roads Corporation has allowed the detailed study of previously undrilled areas, surrounding the Lucky Strike deposit. The study of new drillcore was aimed at testing lateral continuity of the previously defined mine stratigraphy (Thurlow and Swanson, 1987; Barbour *et al.*, 1990). New observations adjacent to the Lucky Strike pit have important implications for drilling targets beneath levels traditionally considered to be prospective (*i.e.*, Buchans River Formation), and provide a better outlook for VMS exploration in Buchans.

BUCHANS GROUP

The Buchans Group (465–462 Ma; Compston, 2000; Zagorevski *et al.*, 2007b) forms part of the Annieopsquotch Accretionary Tract (AAT, van Staal *et al.*, 1998), a collage

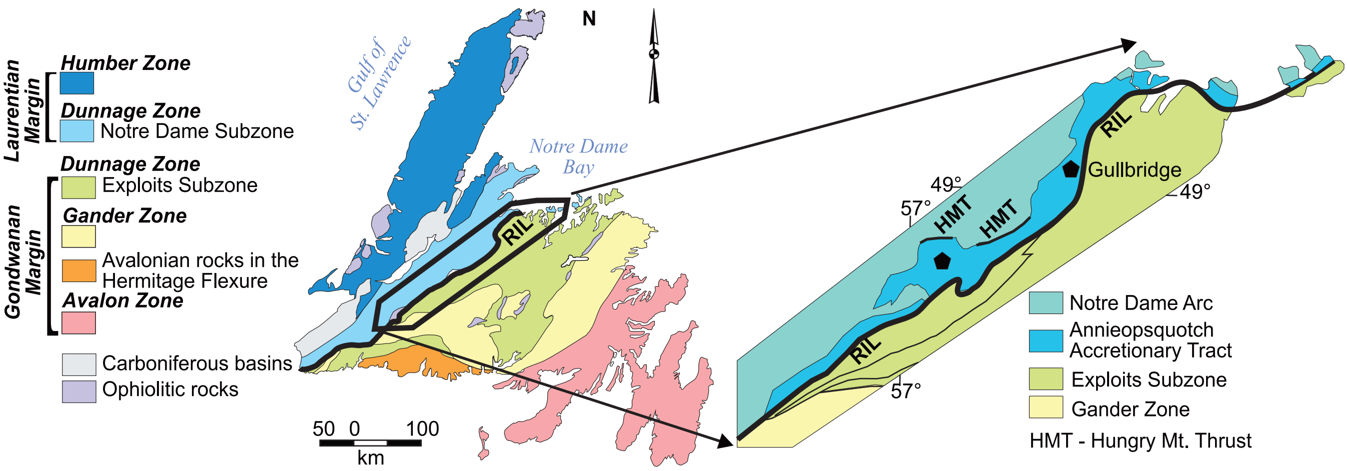


Figure 1. *Position of the Annieopsquotch Accretionary Tract in central Newfoundland, west of the Red Indian Line (RIL), a major suture zone separating rocks of peri-Laurentian (west) and peri-Gondwanan (east) affinity (Zagorevski and Rogers, 2008). Tectonstratigraphic subdivisions of Newfoundland are those proposed by Williams (1988).*

of accreted peri-Laurentian continental arcs and back-arcs formed during the Early to Middle Ordovician (Figure 1). The AAT is bound to the west by the Lloyds River Fault and Hungry Mountain Thrust (Thurlow, 1981; van Staal *et al.*, 1998; Lissenberg *et al.*, 2005), and to the east by the Red Indian Line, a major suture zone separating rocks of peri-Laurentian and peri-Gondwanan affinity (Figure 2; van Staal *et al.*, 1998). The constituent terranes of the AAT were accreted and imbricated along west-dipping, oblique-reverse faults that generally trend northeast–southwest in the Buchans area (Figure 2; *see* Thurlow *et al.*, 1992; Lissenberg *et al.*, 2005; Zagorevski *et al.*, 2007a).

The Buchans Group comprises a fault-bounded arc terrane in the AAT of central Newfoundland, and is structurally overlain by the Harry's River Ophiolite Complex (Zagorevski *et al.*, 2010) and the Notre Dame Arc above the Hungry Mountain Thrust (Zagorevski *et al.*, 2008). To the south, it structurally overlies the Red Indian Lake Group (Zagorevski *et al.*, 2006) along the Tilley's Pond or Powerline fault. To the east it is structurally overlain by the Mary March Brook Formation along the Airport Thrust (Zagorevski *et al.*, 2010; Figure 2).

The Buchans Group is divided into the Lundberg Hill, Ski Hill, Buchans River, and Sandy Lake formations, which combine both felsic and mafic rocks (Thurlow and Swanson, 1987). This grouping of 'local' mafic volcanic rocks within regional felsic volcanic formations creates ambiguity in the current study area (*i.e.*, Lundberg Hill Formation) and makes correlations adjacent to the Lucky Strike deposit difficult. Most of the massive sulphide deposits occur within the Buchans River Formation, which is exposed in a structural window of an antiformal thrust stack with north-dipping ore-bearing duplexes (Figure 2; Calon and Green, 1987). The least structurally disrupted ore-bearing duplex (*e.g.*, Lucky Strike duplex of Calon and Green, 1987) hosts most of the previously mined deposits in the Buchans camp, including the Lucky Strike, Old Buchans, Rothermere, and Maclean orebodies. The Lucky Strike duplex is folded over the culmination of the thrust stack in the Lucky Strike area where it locally has south-dipping attitudes (*e.g.*, Thurlow *et al.*, 1992). The Oriental orebodies, although lying in a separate duplex, are thought to represent thrust-repeated Buchans River Formation and, as such, have been interpreted to occur on the same horizon as the other deposits (Calon and Green, 1987). The complex structural history of the region obscures many of the primary volcanic and sedimentary features and stratigraphic relationships; however, several synvolcanic faults have been identified and an extensional channel/caldera model has been suggested for the Buchans Group (Henley and Thornley, 1981; Kirkham and Thurlow, 1987).

LUNDBERG ZONE

The area surrounding the Lucky Strike (massive sulphide) deposit is divided into the northwest-dipping Lundberg Zone and the south-dipping Engine House Zone (van Hees, 2012). This contribution examines the Lundberg Zone (Figure 3) only. These two zones, previously referred to as the *intermediate footwall,* locally comprise, "a complex, poorly understood stratigraphic package which has been altered extensively and modified significantly by faults" (Thurlow and Swanson, 1987). Although identifying the original rock types is difficult because of the pervasive alteration, the altered mafic volcanic rocks have been placed into the Ski Hill Formation and the felsic volcanic rocks with the

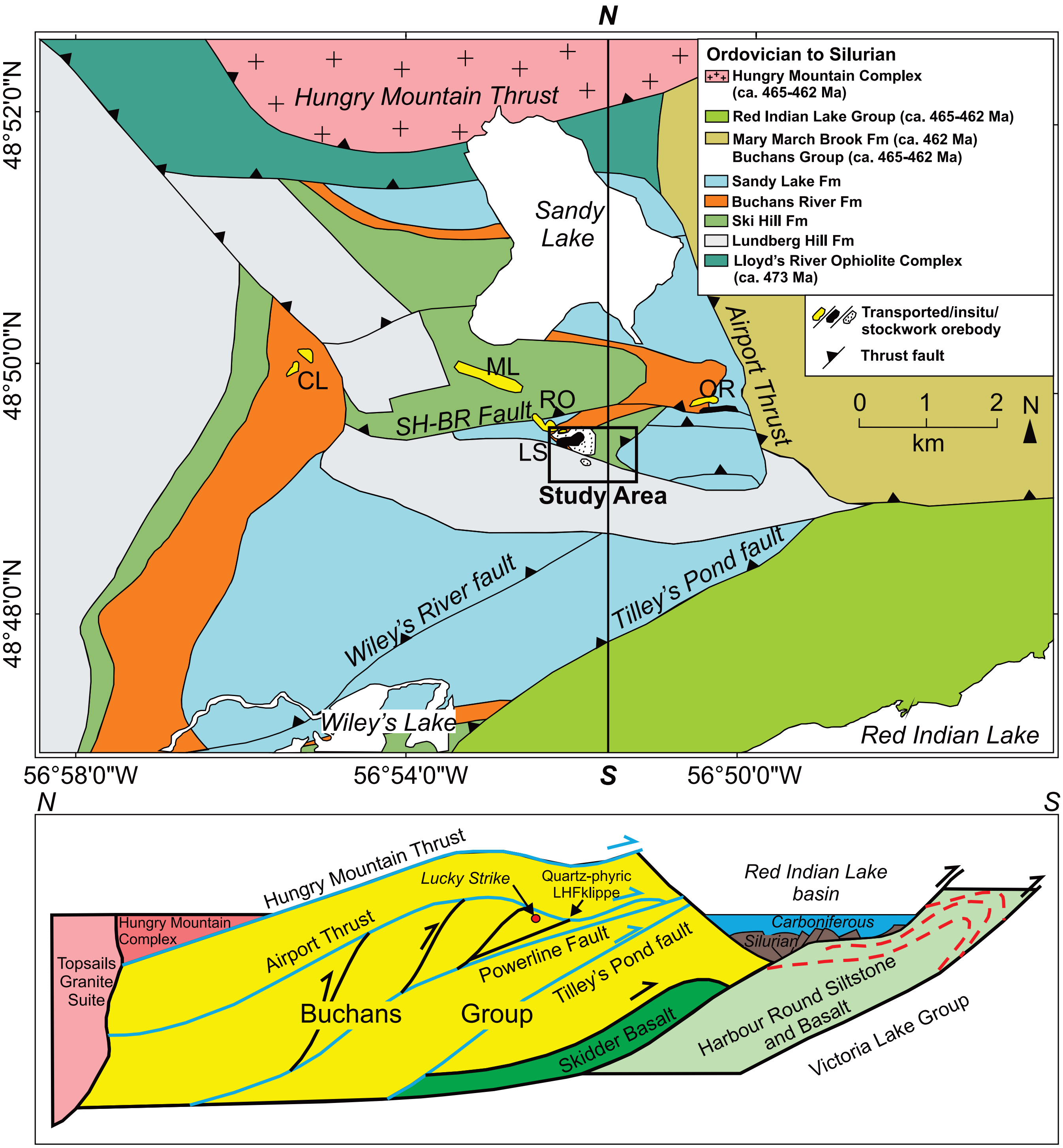


Figure 2. *Compilation map of Buchans geology by Thurlow and Swanson (1987), Thurlow* et al. *(1992), and Zagorevski* et al. *(2009). The mineral deposits (yellow) in the Buchans Group are located along two, broadly northwest- and northeast-trending channels extending away from the Lucky Strike deposit (LS). Rothermere (RO) and Maclean (ML) lie in the north-west channel, whereas the Oriental (OR) and several smaller deposits lie in the northeast channel. The Clementine (CL) prospect lies west of the main deposits. A schematic cross-section (north–south line) of the antiformal thrust-stack model proposed for the Buchans area from seismic and geological data (Thurlow* et al.*, 1992) is shown below the compilation map.*

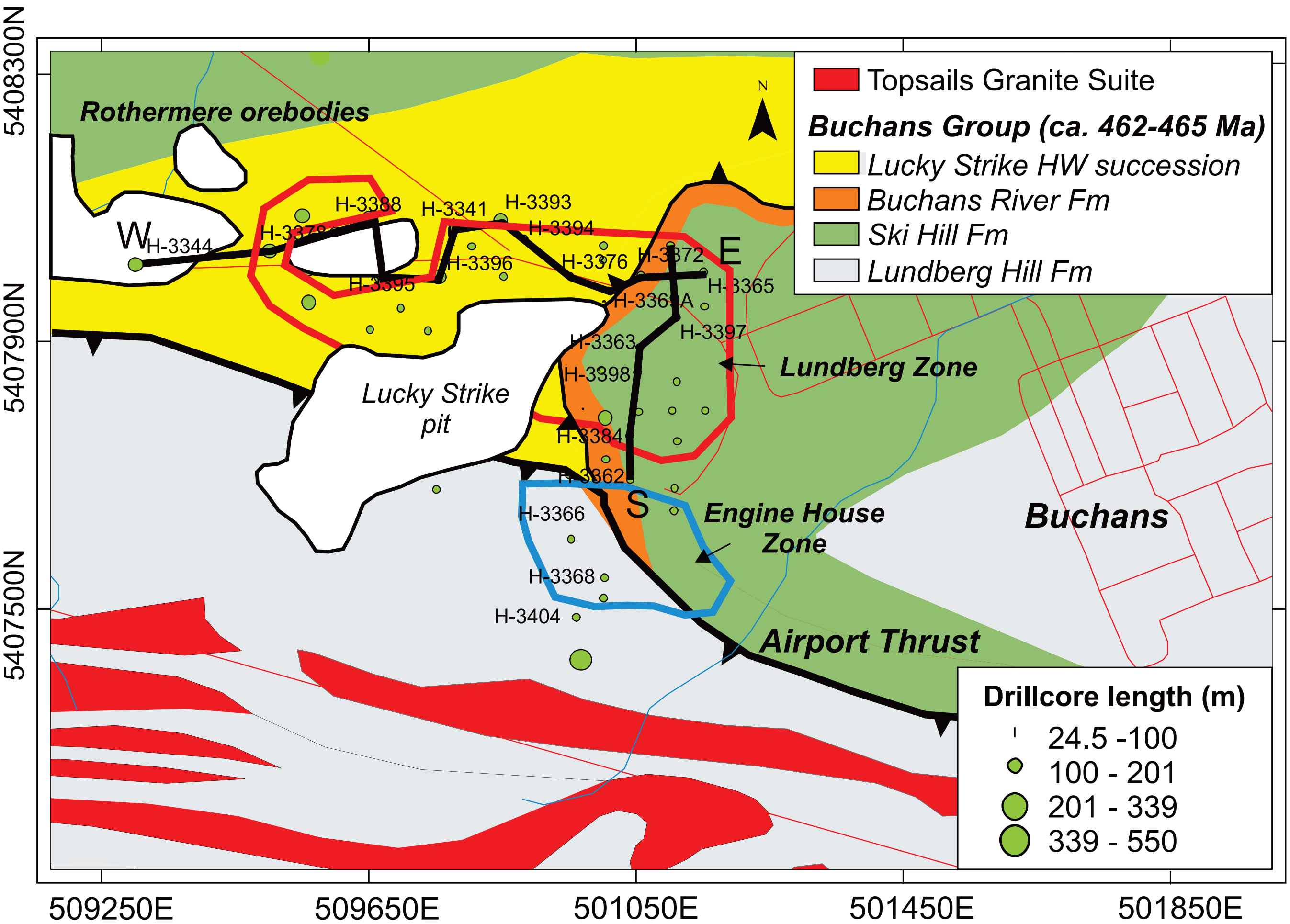
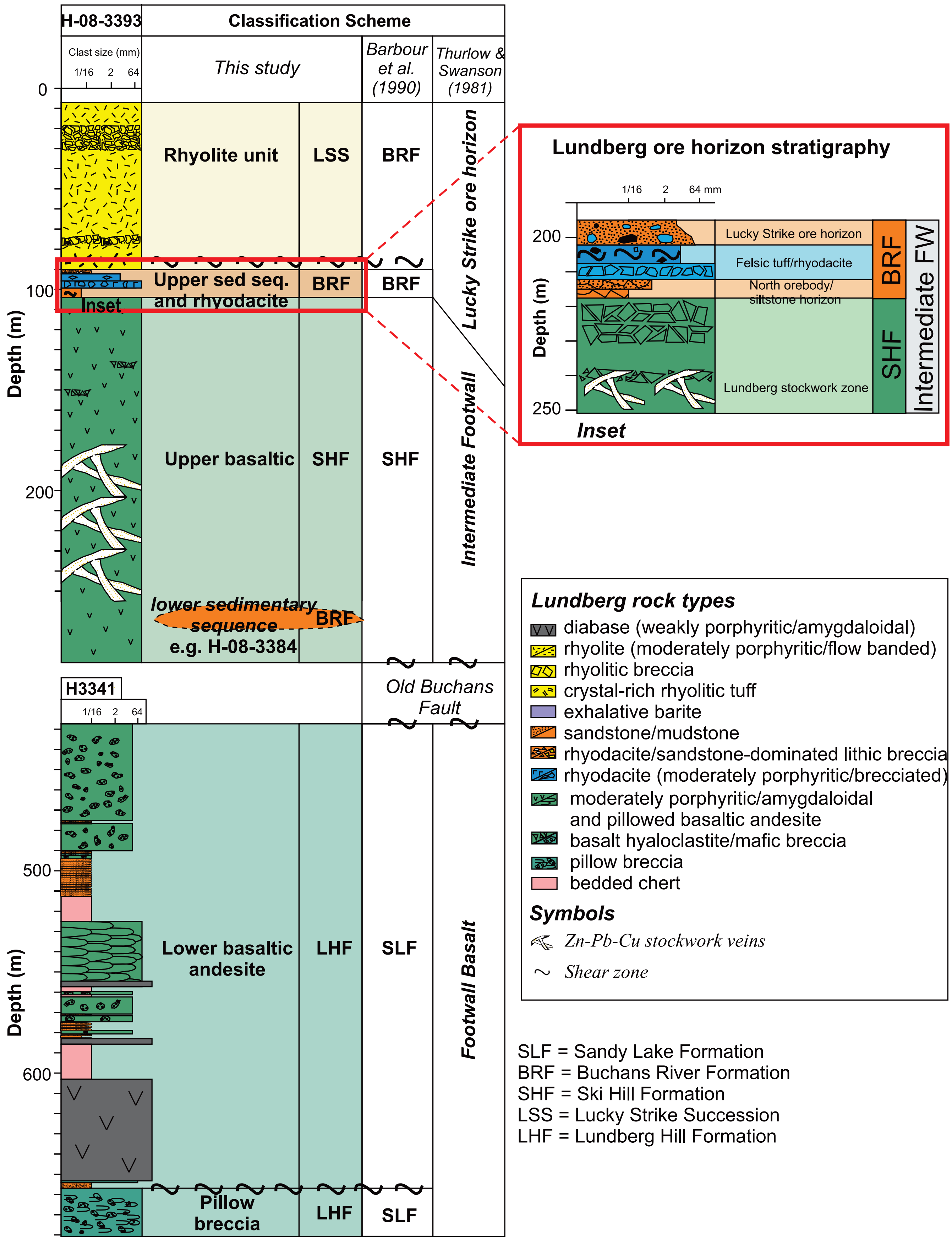


Figure 3. *Local geology of the Lundberg and Engine House zones modified after Davenport* et al. *(1996) including, the surface projection of the mineralization, and the limits of new drilling (Webster and Barr, 2008). West–east and north–south cross-sections are represented in Figure 5 and incorporate the reclassification proposed in the present study (*e.g., *van Hees, 2012).*

Buchans River Formation (Thurlow and Swanson, 1987). The Lundberg Zone includes rocks belonging to both of these formations, with stockwork-style mineralization occurring within the Ski Hill Formation and, to a lesser extent, within the Buchans River Formation, and exhalative mineralization occurring exclusively within the Buchans River Formation (Figure 5). The Lundberg Zone polymetallic stockwork was previously named the 'Lucky Strike Stockwork' and was thought to represent the stockwork to the Lucky Strike deposit (Jambor, 1987). However, it is never observed in contact with the Lucky Strike deposit, as it is separated by a several metre-thick unit of strongly foliated green felsic tuff that forms the immediate structural (and presumed stratigraphic) footwall to the deposit. To the east of Lucky Strike, the stockwork is in abrupt contact with barren rock interpreted to be a flat-lying fault (Jambor, 1987). Nevertheless, massive sulphide ore occurs locally in the Lundberg Zone and is considered to belong to part of the horizon that hosts most of the deposits in the camp.

The stratigraphy of the Lundberg Zone (Figures 4 and 5) consists of seven northwest-dipping units that include basaltic andesite pillows at the stratigraphic base of the zone, the 'lower' and 'upper' basaltic andesite, the upper and lower sedimentary sequences, rhyodacite, and rhyolitic volcanic rocks (van Hees, 2012).

Figure 4. (opposite page) *Stratigraphic nomenclature in the Lundberg Zone area showing its history and development. Details of the ore horizon stratigraphy are shown in the inset. The stratigraphic position of the Lucky Strike ore horizon is identical to that of the Two-level, Rothermere, Oriental, Maclean, and Clementine deposits. The North orebody lies at a slightly lower stratigraphic position than the Lucky strike ore horizon.*



SLF = Sandy Lake Formation
BRF = Buchans River Formation
SHF = Ski Hill Formation
LSS = Lucky Strike Succession
LHF = Lundberg Hill Formation

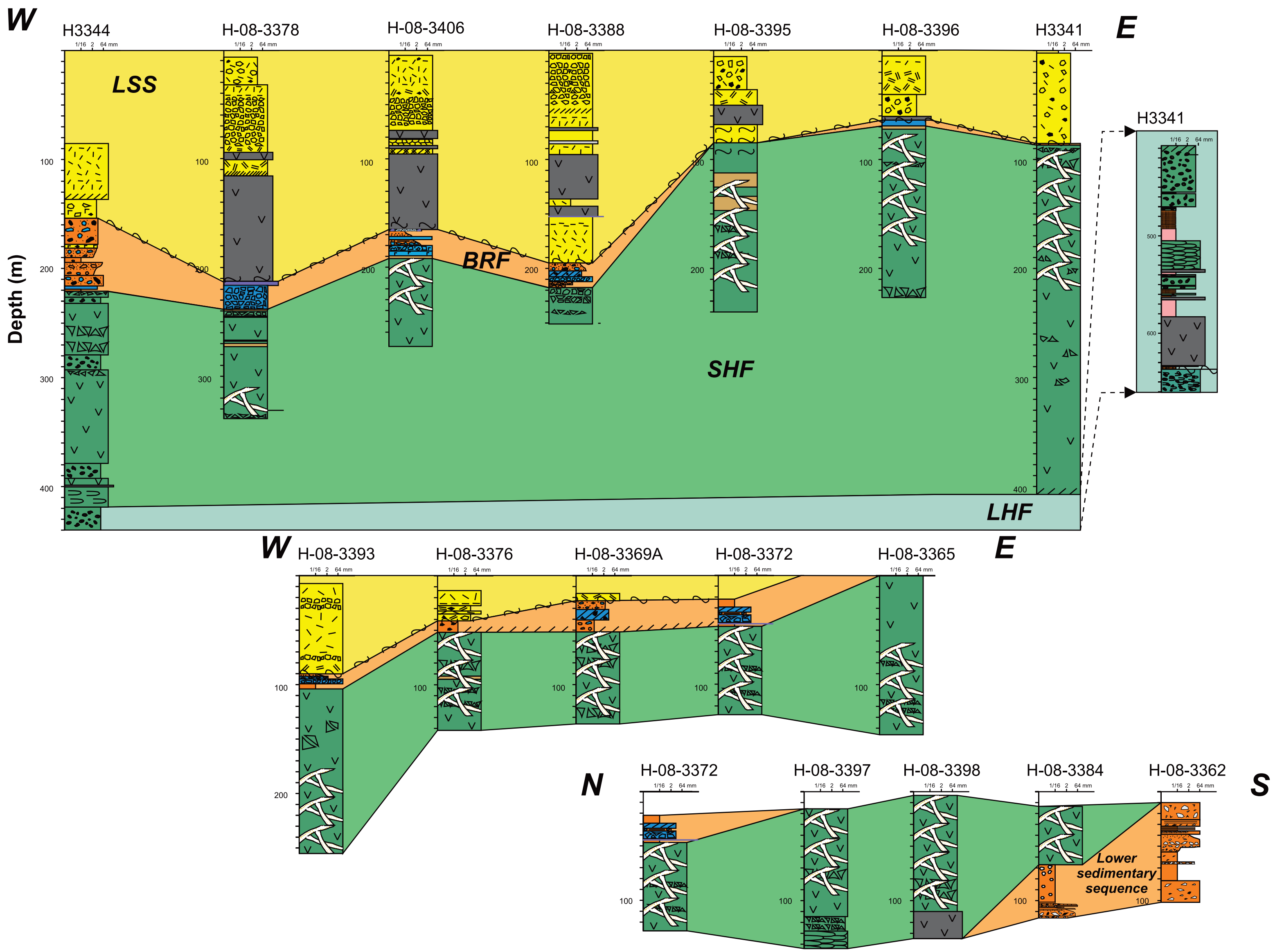


Figure 5. *Geological cross-section west–east and north–south through the Lundberg Zone north of the Lucky Strike open pit. Drillholes are between 50 and 300 m apart. The base of the Lundberg Zone comprises a series of submarine basaltic andesite flows and breccias of the Lundberg Hill (LHF) and Ski Hill (SHF) formations conformably overlain by rhyodacite domes of the Buchans River Formation (BRF) in a local volcaniclastic basin. The top of the succession is marked by a sheared contact intruded by diabase sills and overlain by rhyolite flows and tuff of the Lucky Strike hanging-wall succession (LSS). The lower sedimentary sequence within the Buchans River Formation is observed in drillholes H-08-3384 and H-08-3362.*

LEGEND (For Figures 5–12)

Lundberg rock types

- diabase/intermediate dyke (weakly porphyritic/amygdaloidal)
- rhyolite (moderately porphyritic/flow banded)
- rhyolitic breccia
- crystal-rich rhyolite tuff
- exhalative barite
- 'hydrothermal upflow zone'
- sandstone/mudstone
- sandstone/polylithic breccia
- rhyodacite (moderately porphyritic/brecciated)
- rhyodacite (aphyric/rhyodacite tuff)
- moderately porphyritic/amygdaloidal and hyaloclastite basalt
- bedded chert
- mafic breccia/pillow breccia

Symbols

- *Zn-Pb-Cu stockwork veins*
- *Shear zone*
- *Brittle fault zone*

Basaltic Andesite Pillow Breccia

The pillow breccia unit, which forms the stratigraphic base of the Lundberg Zone, consists of scoriaceous basaltic andesite pillow fragments that display chilled margins characteristic of fragmented pillow margins, flows, or bombs (Figure 6A). Contacts with the overlying basaltic andesite are sheared and in a few areas marked by abundant diabase sills.

Lower Basaltic Andesite

The lower basaltic andesite overlies the basaltic andesite pillow breccia in the Lundberg Zone and is primarily composed of pillowed basaltic andesite and lesser mafic breccia, turbidites and multicoloured chert (Figure 6). Contacts between these rocktypes are marked by sharp, often scoured basal contacts where mafic breccia or turbidites overlie chert and planar contacts, and chert overlies mafic breccia or turbidites.

The multicoloured chert is characteristically laminated to thin bedded and, ranges from grey, beige, olive-green, pale-yellow, orange, hematitic-red, and dark purple-black (Figure 6B). Contacts between chert beds are typically sharp and planar, but a few contacts are defined by rare ball and pillow structures (Figure 6B). The minimum thickness of the chert unit is 34.7 m.

Amygdaloidal pillow basaltic andesite overlies chert across a contact intruded by diabase sills. Pillow selvages are 3 to 4 cm thick and form predominantly black, arcuate bands and triple junctions, although various shades of red and purple are also observed. Mafic breccia locally forms metre-scale layers that have scoured basal contacts and reversely graded and normally graded tops. Rare, rounded chert clasts occur near the top of the breccia. The mafic breccia is an altered, medium-grained, feldspathic unit containing subrounded scoriaceous basaltic andesite clasts and common chloritic mudstone interbeds less than 10 cm thick (Figure 6C). Clast abundance ranges from <5 to 30%; clasts typically average 3 to 4 cm in diameter, but can be as much as 20 cm. The clasts have sharp, irregular contacts and consist of carbonate-infilled scoria (Figure 6C).

The mafic-derived, thick-bedded turbidites consist of stacked greenish-grey T_{ad}, T_{bd}, T_{abd}, or T_{acd} divisions of the Bouma sequence (Bouma, 1962). Individual stacks of T_{ad},

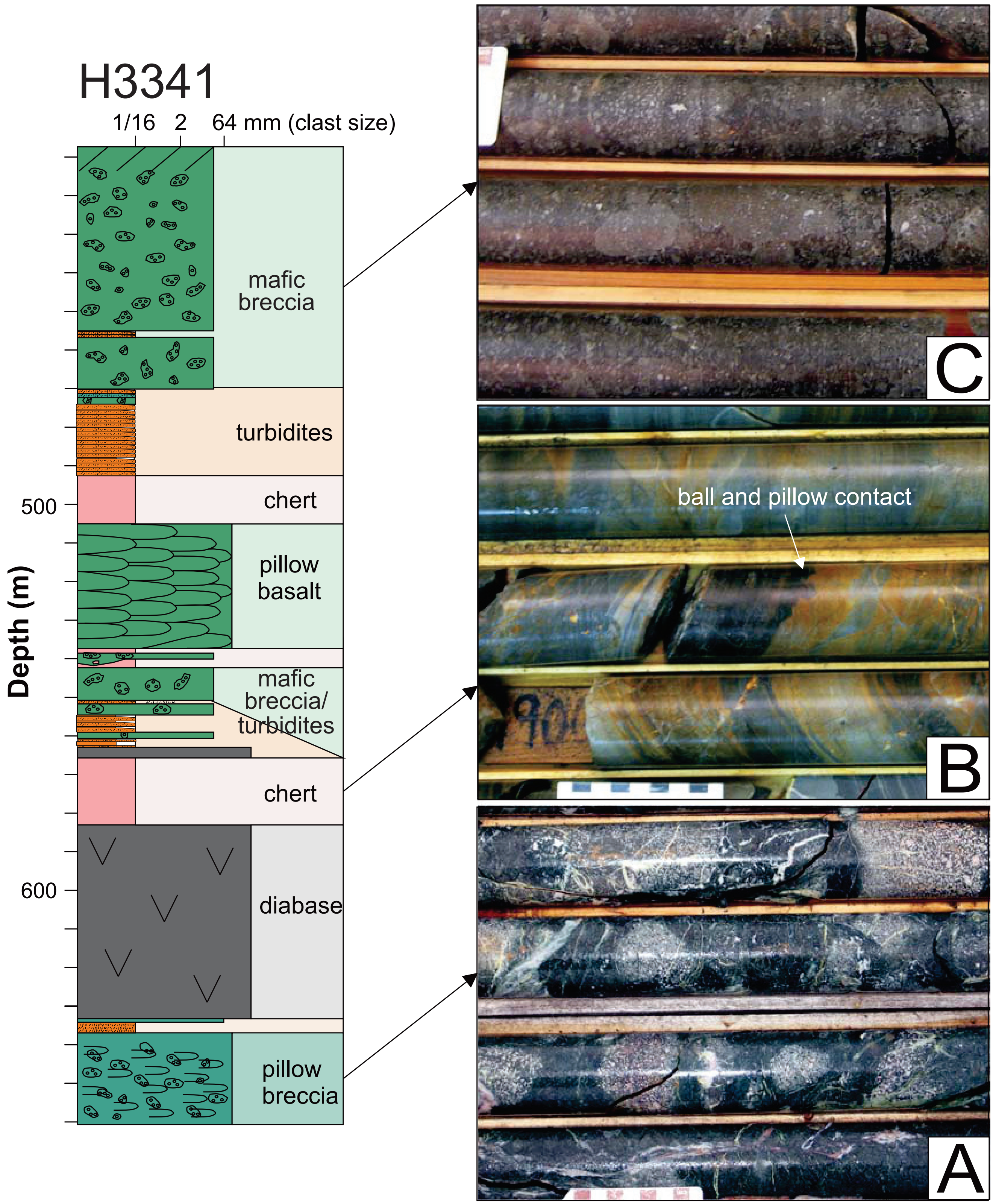


Figure 6. *Summary of the stratigraphic relationships of the lower basaltic andesite unit. Diameter of drillcore in all photographs is 4.76 cm. A) Pillow breccia unit with distinctly chilled margins evident in some clasts* (e.g., *hole 3368;125 m; top right). B) Ball and pillow structure within 'bedded chert' indicating siliciclastic sedimentation and later silicification (hole 3341; 579.3 m). C) Mafic tuffaceous unit with unique ungraded scoriaceous basaltic andesite clasts (H3344; 259.2 m).*

T_{bd}, T_{abd}, or T_{acd} turbidites average about a metre, but range up to 2.1 m in thickness.

Upper Basaltic Andesite Member

The upper basaltic andesite stratigraphically overlies the lower basaltic andesite in the Lundberg Zone. It consists primarily of massive to feldspar or clinopyroxene porphyritic, and amygdaloidal basaltic andesite with common hyaloclastite and flow breccia (Figure 7A). At its stratigraphic top, the basaltic andesite is more andesitic. Contacts between the upper and lower basaltic andesite members are heavily altered and are marked by a significant decrease in tuffaceous rocks.

The massive, beige- to black-basaltic andesite is feldspar or clinopyroxene phenocrystic and/or glomeroporphyritic (<5 to 30 vol.%) and contains approximately 15% amygdales. The matrix has a prominent trachytic texture of variably altered feldspar microlites, although a highly vesicular to scoriaceous texture is common. Hyaloclastite is common, forming intervals ranging from 30 cm to greater than 10 m thick (Figure 7A). Perlitic basaltic andesite to andesite fragments are exclusively black and form arcuate to angular clasts averaging 1 cm in diameter but ranging up to 3 cm in diameter. The hyaloclastite is frequently brecciated *in situ*, with angular clasts ranging from <1 cm up to decimetres, and forming jig-saw-fit patterns. Andesite horizons occur at the top of the sequence and consist of beige volcanic rocks, and emerald-green, muscovite-altered feldspar phenocrysts (Figure 7C). The andesite is discontinuous throughout the stratigraphy and is difficult to differentiate from basaltic andesite.

Lower Sedimentary Sequence

The lower sedimentary sequence forms a 110-m-thick conformable lens within the upper member of the basaltic andesite (Figure 5). It comprises a basal unit of altered and/or graded rhyodacite-dominated breccia, which is conformably overlain by a thick succession of siltstone with interstratified rhyodacite breccia and a massive rhyodacite-dominated breccia.

The altered rhyodacite-dominated breccia at the base of the sequence forms matrix-supported beds that are typically massive, or less commonly, reversely graded. Clasts comprise 30 vol.% of the rock and form three distinct clast populations. Feldspar-phyric (5 vol.% of clast) to aphyric and flow-banded rhyolitic to rhyodacitic clasts are most abundant (90% of clast population) and are typically cobble size (<20 cm; Figure 8A). Feldspar porphyritic (<10 vol.% of clast) to aphyric basaltic andesite clasts (10%) are medium-, to dark-grey, subrounded angular cobbles (~3-4 cm in size) to large pebbles (1 cm in size). Sulphide clasts are the least abundant (<1%), consisting of massive pyrite or galena blebs, 1 cm or less in length. The matrix consists of angular, lithic fragments (50 vol.% of matrix) less than 1 cm in length, and are similar in composition and proportions to the larger clast population. Black, irregular-shaped blocks and rare curviplanar chloritic fragments make up 10% of the matrix and may represent hydrated and altered glass.

Siltstone with discrete, metre-scale interbeds of rhyodacitic breccia (15 total vol.%) overlies the basal rhyodacite-dominated breccias (Figure 8A). These beds are clast-supported (>80% clasts) and are dominated by 3-cm-diameter, white aphyric rhyodacite clasts, and rare (<1 cm) massive sphalerite–galena clasts in a black chloritic (± pyritic) siltstone matrix. Massive beds are most common. Lower contacts between these layers are typically sharp and scoured, and in rare cases, are underlain by plane-bedded siltstone to fine-grained sandstone (Figure 8B). Upper contacts are typically sharp and irregular but also locally grade into diffuse, clast-bearing horizons (10% clasts) above the main clast-supported bed.

The uppermost unit of the lower sedimentary sequence is a massive rhyodacite-dominated polymictic breccia (>85 total vol.%) with interbedded, normal-graded to planar-laminated sandstone to siltstone (<10 vol.%) and re-sedimented basaltic andesite hyaloclastite (<5 vol.%, Figure 8C). The polymictic breccia consists of approximately 65% altered matrix, and 35% clasts. Clasts comprise three major types. The dominant clast population is flow-banded rhyodacite (75-80% of clast population) defined by irregular light greyish-white and dark-grey bands. Basaltic andesite clasts (15%) and sandstone and siltstone clasts (5 to 10%) are similar to those in the basal rhyodacite-dominated breccias. The matrix consists of coarse-grained silt to sand-sized detritus.

The interbedded sandstone and siltstone unit forms the typical T_{ab} division of the Bouma sequence and consist of normal-graded, medium- to fine-grained sandstone averaging 10 cm in thickness (T_a division), grading upward to a planar-laminated horizon, averaging 5 cm in thickness with maximum thicknesses up to 20 cm (T_b division; Figure 8C). T_{ab} stacks grade from thick (up to 30 cm) and abundant directly overlying the siltstone-dominated lower unit, to thin-bedded (10 to 15 cm) and rare in the stratigraphically highest sections, marking a distinct change in depositional conditions. Intercalated with the sandstone and siltstone is a resedimented mafic hyaloclastite that forms rare 1- to 3-m-thick layers (Figure 8C).

Rhyodacite

The rhyodacite unit conformably overlies the upper

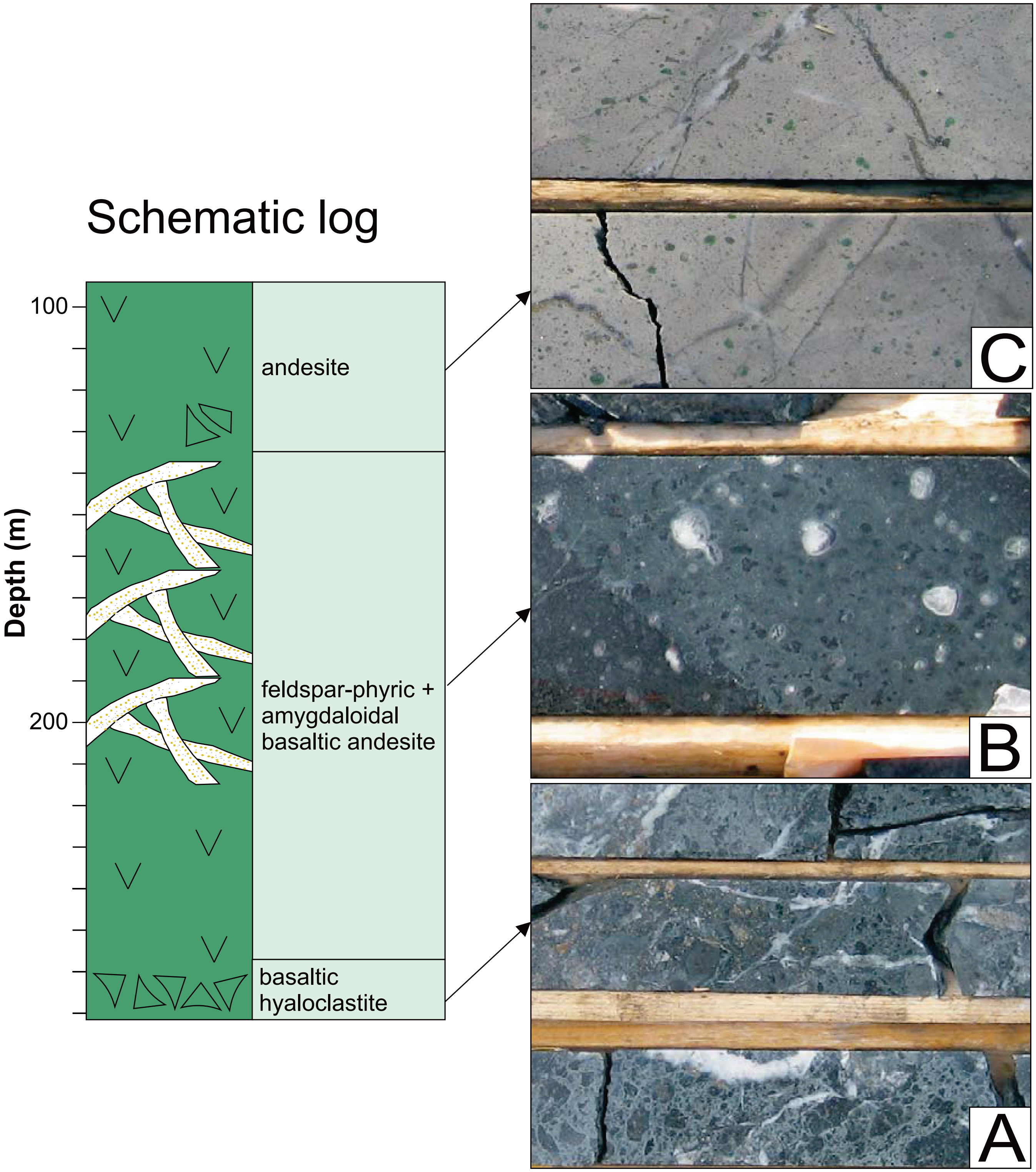


Figure 7. *Summary of the stratigraphic relationships of the upper basaltic andesite unit. Diameter of drillcore in all photographs is 4.76 cm. A) Hyaloclastite with* in situ *brecciation of highly amygdaloidal basaltic andesite (quartz–hematite–carbonate–chlorite alteration; H3396; 227 m). B) Feldspar porphyritic and quartz–carbonate-altered amygdaloidal upper basaltic andesite (H3386; 141.5 m). C) Emerald-green, muscovite-altered feldspar phenocrysts of the andesite unit.*

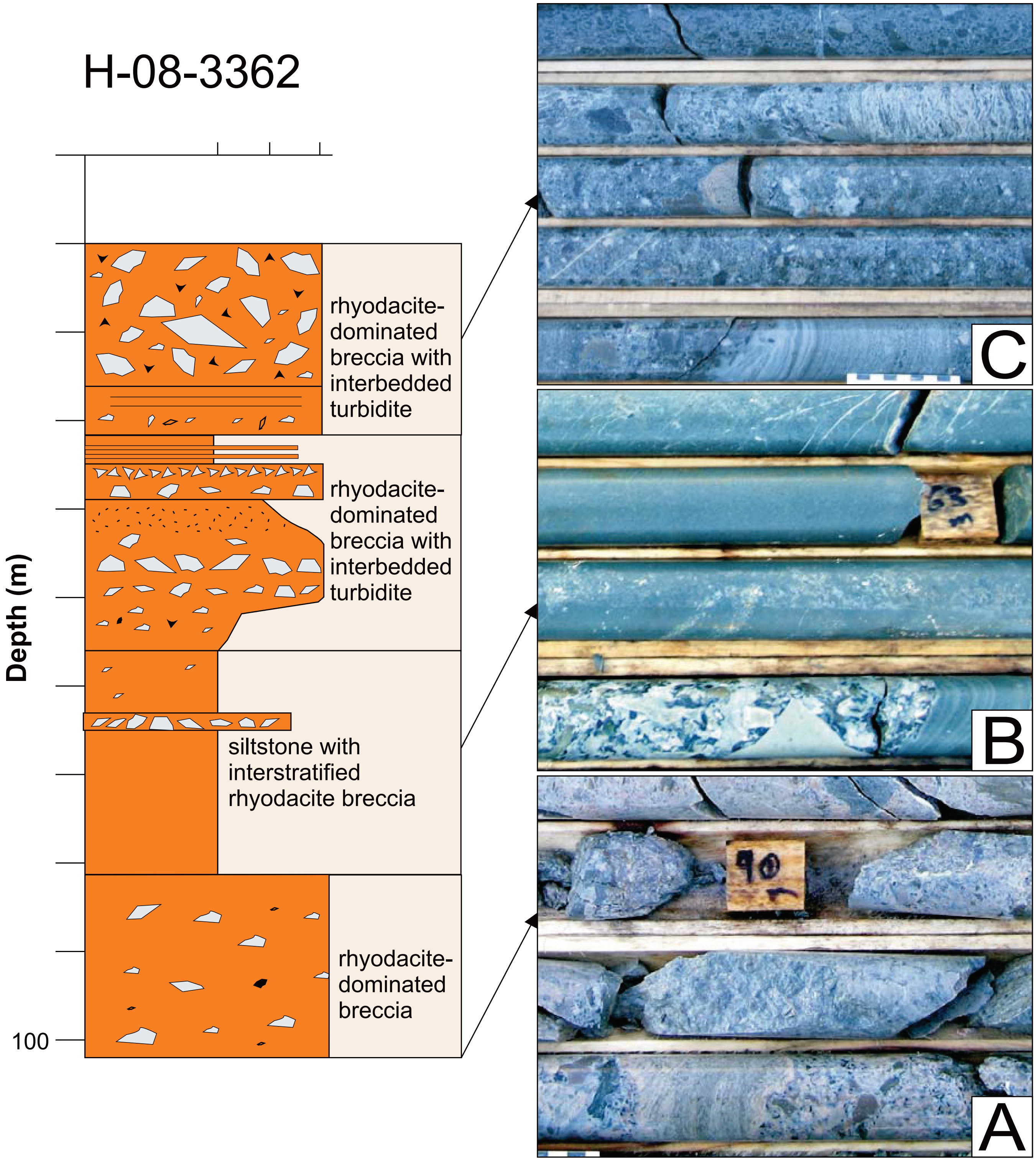


Figure 8. *Summary of the stratigraphic relationships of the lower sedimentary sequence. Diameter of drillcore in all photographs is 4.76 cm. The sequence records a shift from proximal rhyodacite-dominated breccia (A: H3362; 90 m) to more distal massive siltstone (B: H3362; 65 m). The occurrence of rhyodacite mass flow breccias with interbedded turbidites at the top of the unit suggests reactivation of the volcanic edifice. C) T_{abc} Bouma division turbidite among polymicitc debris flow (H3362; 28 m). The resedimented hyaloclastite is observed in the top row of Figure 8C, highlighting the increase in mafic clasts in the upper portions of the lower sedimentary sequence.*

basaltic andesite member and occurs only in holes H-08-3378 and H-08-3406 of the Lundberg Zone. The rhyodacite is sparsely porphyritic and characterized by brecciation and intense hydrothermal alteration. Contacts between these two units are often obscured by a gradational colour change from light-grey to dark-grey-black due to alteration of the rhyodacite and underlying basaltic andesite, making separation of the units difficult. As well, the rhyodacite unit is locally sheared and altered in discrete zones up to 33 m thick. Many primary textures within the rhyodacite have been obliterated.

The rhyodacite comprises light-beige to grey, massive flows and breccia and is up to 30 m thick. It is commonly cherty, flow banded, and contains 5 to 15% variably altered feldspar (1 to 2 mm) and quartz (average 0.25 to 0.5 mm, up to 1 mm) phenocrysts. Quartz displays micropoikylitic, embayment and resorption textures. In hole H-08-3406, the rhyodacite grades vertically into rhyodacitic sandstone/ wacke and siltstone.

Two types of related breccias are observed within the rhyodacite that include autobreccia and jig-saw-fit breccia. The autobreccia is characterized by blocky and angular rhyodacite clasts, 5 to 10 cm in diameter, occurring throughout the unit. *In situ* brecciation is characterized by jig-saw-fit texture of clasts averaging 4 cm in diameter but reaching up to 40 cm (Figure 9A). The rhyodacite is overlain by a discontinuous 0.1- to 3.9-m-thick barite bed and/or volcanosedimentary sequence (Figure 9B).

Upper Sedimentary Sequence

The upper sedimentary sequence consists of altered to unaltered matrix-supported rhyodacite-dominated breccia overlain by siltstone intercalated with rhyodacite-dominated breccia, intensely altered rhyodacite tuff, and clast-supported rhyodacite polymictic breccia. The upper sedimentary sequence overlies the basaltic andesite or rhyodacite with sharp, undulating contacts.

The basal rhyodacite-dominated breccia of this sequence forms 2.1- to 14-m-thick beds above a sharp and undulating contact with mafic breccia and consists of 70% silicified coarse silt to sand matrix and 30% clasts (Figure 9C). Four clast types were identified including rhyodacite, basaltic andesite, sedimentary, and massive sulphide. These clasts are lithologically similar to those found in the lower sedimentary sequence and have similar abundances. Overlying the altered rhyodacite-dominated breccias, across a sharp contact, are siltstone and sandstone beds that have variable felsic volcanic clast abundances, or black mudstone beds. The thicknesses of these beds are also variable, forming 2- to 12-m-thick successions of *in situ*, brecciated sandstone and siltstone, black mudstone, or both (Figure 10A). The *in situ* breccia comprises interlocking clasts of various grain sizes (medium-grained sandstone to siltstone) with irregular to subangular clast margins. Rare, white rhyodacite (1 to 5%) and black aphanitic basaltic andesite (<1%) clasts in the sandstone breccia matrix are 4 cm or less in size.

The intensely altered rhyodacite tuff is unique to the upper sedimentary sequence and overlies the sandstone to siltstone breccia across a sharp contact. It consists of flow-banded, sericitized feldspar phenocrysts (>50 total vol.%), rounded quartz phenocrysts (20 total vol.%), lithic and/or pyroclastic fragments, and abundant disseminated pyrite (Figure 10B). The tuff is fine bedded, defined by the alignment of pyroclasts, lithic fragments, and clay minerals observed in the matrix. The matrix is composed of fine-grained, hydrothermally altered quartz and carbonate, or clay minerals and probably represents a volcanic ash component.

The upper contact of the rhyodacite polymictic breccia unit is sharp and typically sheared, and is marked by zones containing rare, barite-bearing massive sulphide and sulphide-rich clasts up to 70 cm in thickness. The lower contact is sharp and undulating. The breccia beds are typically massive and consist of a single 5-m-thick bed or two stacked beds. The breccia is characterized by >70% clasts in a grey, pyritic siltstone to coarse sandstone matrix. Five distinct populations of clasts are recognized. Rhyolitic to rhyodacitic clasts (70% of clast population) are angular to subrounded, feldspar-phyric (<5 to 30 vol.%) to aphyric and cherty, and vary from red, beige, to grey. Basaltic andesite clasts (15 to 20% of clast population) are black, commonly altered, sparsely plagioclase phyric, and contain 5 to 10% quartz, carbonate, and pyrite-filled amygdales. Claystone and fine-sandstone comprise 10 to 15% of the clasts. The claystone clasts consist of quartz and feldspar grains ranging from <3 μm up to 8 μm in length with rare pyrite grains containing blebby sphalerite inclusions up to 24 μm. Rare biotite–granodiorite clasts are also observed. Sphalerite, galena, chalcopyrite, and pyrite occur as rounded clasts, <1cm in diameter. The matrix of the breccia is composed mostly of angular quartz and feldspar grains and lithic fragments (0.3 mm average size) displaying both volcanic (embayment and resorption) and plutonic (*e.g.*, granophyric) textures in an irregularly sericitzed clay matrix (45 vol.% of matrix).

Rhyolite

The uppermost rhyolite unit structurally overlies the upper sedimentary sequence in the Lundberg Zone. The rhyolite is aphanitic to quartz-feldspar porphyritic and is typically massive near the base and brecciated in the stratigraphically higher levels and is interlayered with crystal-

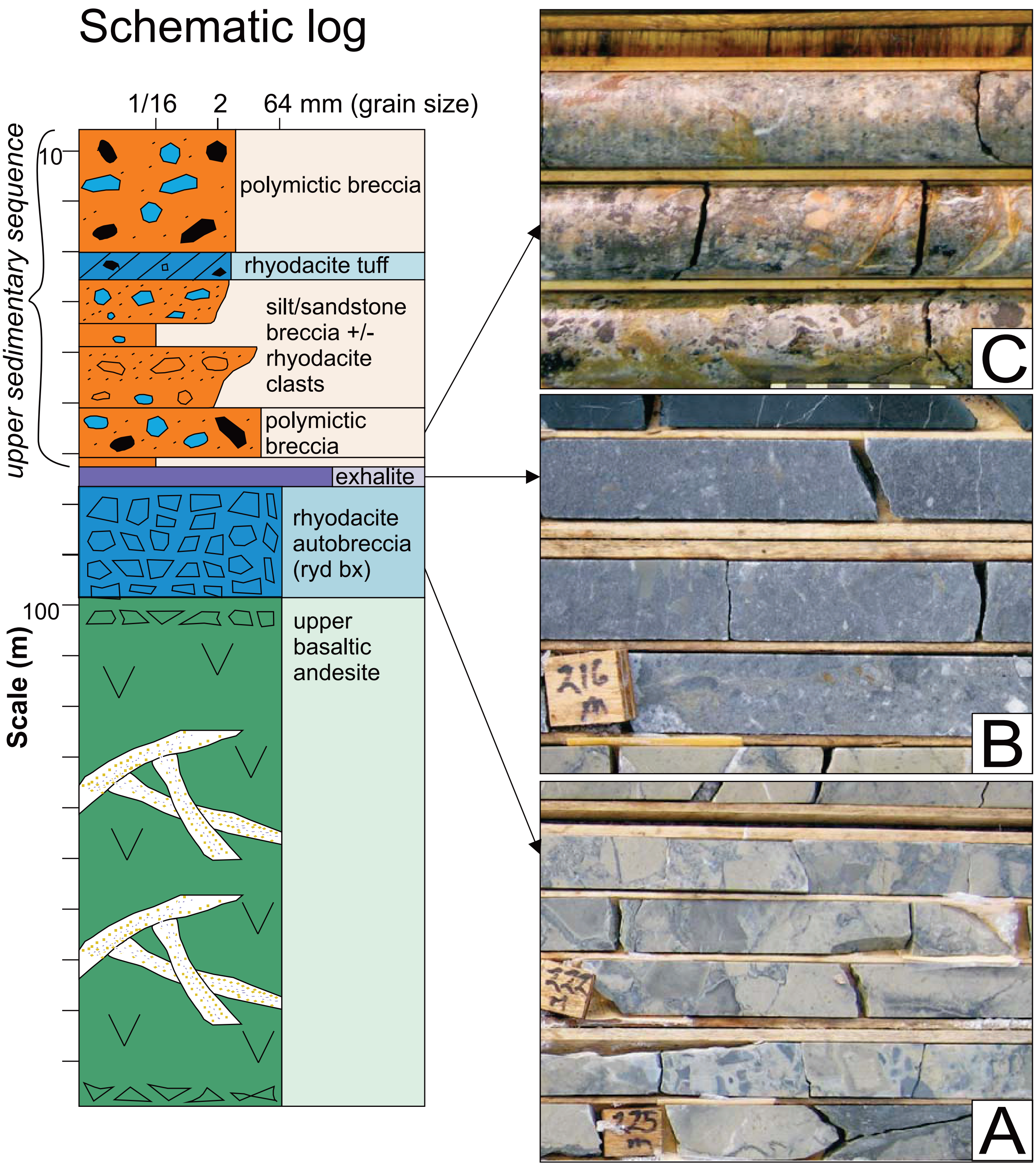


Figure 9. *Stratigraphic position of the rhyodacite, exhalite, and heavily altered basal polymictic breccia of the upper sedimentary sequence. Diameter of drillcore in all photographs is 4.76 cm. A)* In situ *jig-saw-fit rhyodacite breccia with a silicified fine-grained matrix (H3378; 220 m). B) Bedded barite with rare rhyodacite clasts, large euhedral barite crystals, and disseminated sphalerite and galena (H3378; 216 m). C) Silicified basal polymictic breccia of the upper sedimentary sequence (H3344; 210 m).*

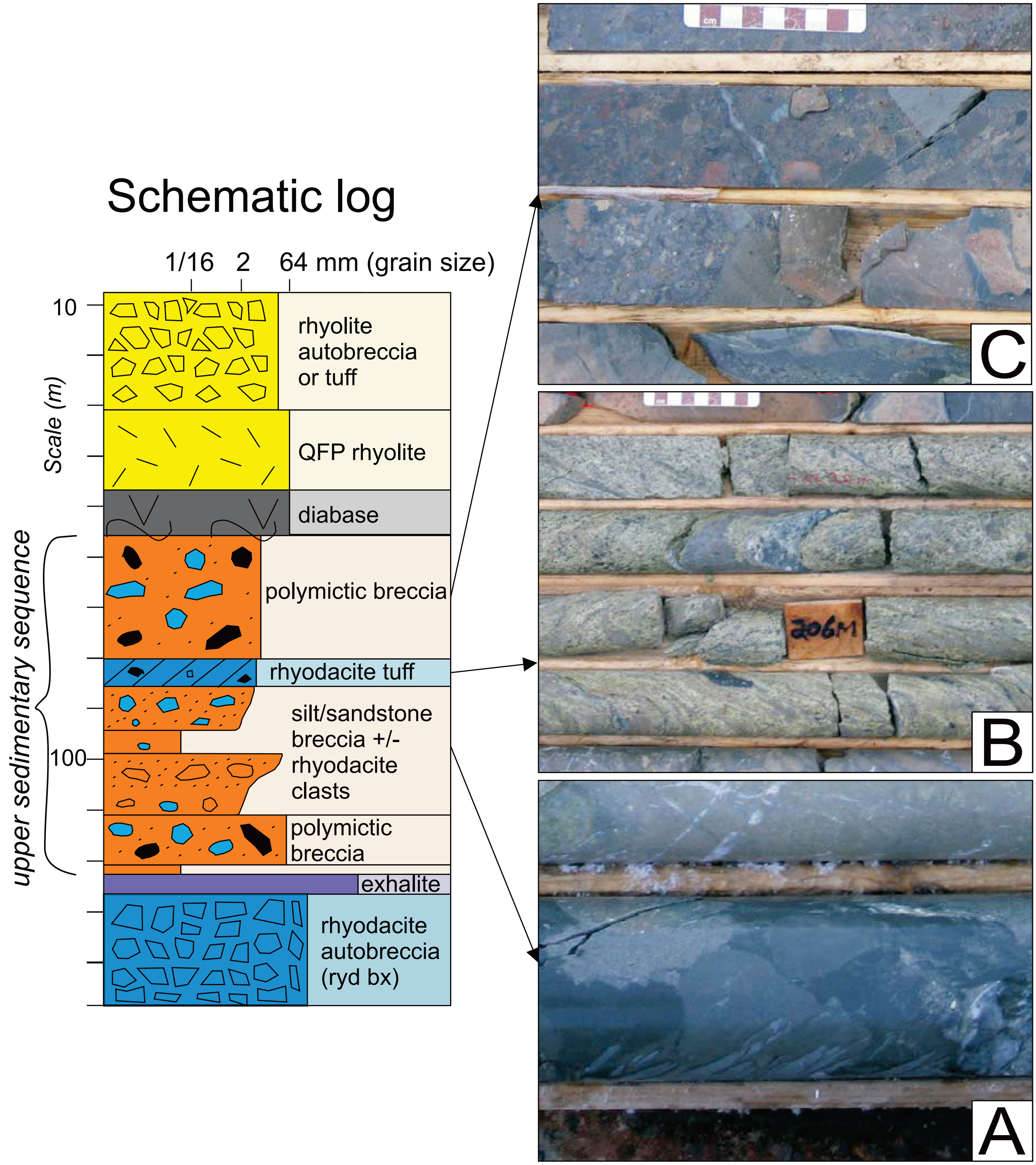


Figure 10. *Summary of the stratigraphic relationships of the upper sedimentary sequence. Diameter of drillcore in all photographs is 4.76 cm. A) Brecciated fine-grained sandstone and siltstone formed by slumping of unconsolidated sediments (H3388, 213 m). B) Crystal-rich rhyodacitic tuff with lithic fragments and fiamme? (H3388; 206m). C) Polymictic breccia with rare 1 cm massive sphalerite-galena clasts (top left) and abundant angular rhyodacitic clasts (H3388; 197 m).*

rich tuff. The lower contact with rhyodacite and the upper sedimentary sequence is typically sheared, altered, and largely obscured by late diabase sills.

Massive rhyolite contains 30 to 70% euhedral to subhedral white feldspar phenocrysts, (<2 mm in length) commonly displaying glomeroporphyritic texture. Rounded, grey quartz phenocrysts (<2 mm in size) range in abundance from <5 to 30% but typically <10% (Figure 11A). Flow banding is common within the massive unit and is defined by alternating red and black bands averaging 1 cm thick. Other textures observed in drillcore and in thin section include granophyre, graphic intergrowths, perlite, and embayed and resorbed phenocrysts. Embayed and resorbed quartz and feldspar grains/phenocrysts are particularly common in all analyzed thin sections; however, perlitic fracture is extensive only in the massive flow-banded unit and in thin sections containing granophyric texture. Epidote, prehnite, and pumpellyite were identified as metamorphic replacements of felsic volcanic glass. Rare, primary amphibole phenocrysts were observed, which are commonly pseudomorphed by chlorite.

Brecciated rhyolite is characterized by both aphanitic and porphyritic subrounded, altered rhyolitic clasts (Figure 11B). Rhyolitic clasts (10 to 50%) average 3 to 5 cm in diameter, but locally are 10 cm (Figure 11B). In rare stratigraphic sections, basaltic andesite clasts form 10 cm, subangular, feldspar-phyric clasts that have altered margins up to 4 cm thick. Crystal-rich rhyolitic tuff occurs throughout this unit. It typically contains >70 vol.% feldspar with lesser quartz phenocrysts and rare angular jasper and rhyolite clasts <1 cm in diameter (Figure 11C).

CORRELATION WITH THE BUCHANS STRATIGRAPHY

At the base of the Lundberg Zone, Barbour *et al.* (1990) assigned the pillow breccia and lower basaltic andesite to the Sandy Lake Formation (SLF), the structurally overlying upper basaltic andesite to the Ski Hill Formation (SHF), and the overlying rhyodacite, upper sedimentary sequence, and rhyolite to the Buchans River Formation (BRF) (Figure 4). Based on the observations of this study (van Hees, 2012), the pillow breccia and lower basaltic andesite are reassigned to the Lundberg Hill Formation, the upper basaltic andesite of the Ski Hill Formation, and the rhyodacite and upper sedimentary sequence of the Buchans River Formation retain their original definition, and the rhyolite unit is placed into an informal *Lucky Strike hanging-wall succession*.

Lundberg Hill Formation

Barbour *et al*. (1990) grouped the pillow breccia and lower basaltic andesite into the Sandy Lake Formation; however, they are reassigned here to the Lundberg Hill Formation (Figure 4). The Sandy Lake Formation is thus unobserved in the present study area. In the Lucky Strike area, the Lundberg Hill Formation consists of bedded tuffaceous sedimentary rocks with unique multicoloured chert beds (Thurlow and Swanson, 1987). These unique chert beds are observed at the base of the Lundberg Zone succession and suggest that the lower basaltic andesite be grouped into this formation. Additionally, the contact between the lower and upper basaltic andesite is only weakly sheared and altered and appears conformable; rather than a major thrust contact as previously proposed (Figure 4, Old Buchans Fault of Barbour *et al*., 1990). Without the imposed thrust, the underlying basaltic andesite must be grouped with the Ski Hill Formation, or assigned to the Lundberg Hill Formation; due to unique lithological differences, we adopt the later.

Ski Hill Formation

The massive and brecciated basaltic andesite are grouped into the Ski Hill Formation; consistent with previous definition (Barbour *et al*., 1990). The lower contact with the Lundberg Hill Formation is weakly sheared and altered and thought to be conformable, whereas the upper contact is clearly conformable with Buchans River Formation. Toward the top of the Ski Hill Formation, the andesite found here, is slightly more fractionated than the upper basaltic andesite. This andesite horizon forms only part of the previous ‘Intermediate Footwall’. The Ski Hill Formation is conformably overlain by the rhyodacite and upper sedimentary sequence, which host the Lucky Strike deposit and are grouped into the Buchans River Formation.

Buchans River Formation

The lower and upper sedimentary sequences, and the rhyodacite are grouped into the Buchans River Formation. The lower sedimentary sequence forms a lens within the Ski Hill Formation, and may correlate with the ‘Marginal Footwall Arkose’, which locally underlies the ‘Intermediate Footwall’ in the Lucky Strike area (Thurlow and Swanson, 1981). The conformable upper contact between the lower sedimentary sequence and the upper basaltic andesite indicates that no thrust faults are present and either the Buchans River Formation is interfingered with the Ski Hill Formation (*i.e.*, time transgressive) or there are other sequences similar to those found in the Buchans River Formation lower in the stratigraphy. The lower contact remains undrilled.

Lucky Strike hanging-wall succession

Barbour *et al.* (1990) grouped the rhyolite unit at the top of the sequence with the Buchans River Formation, and

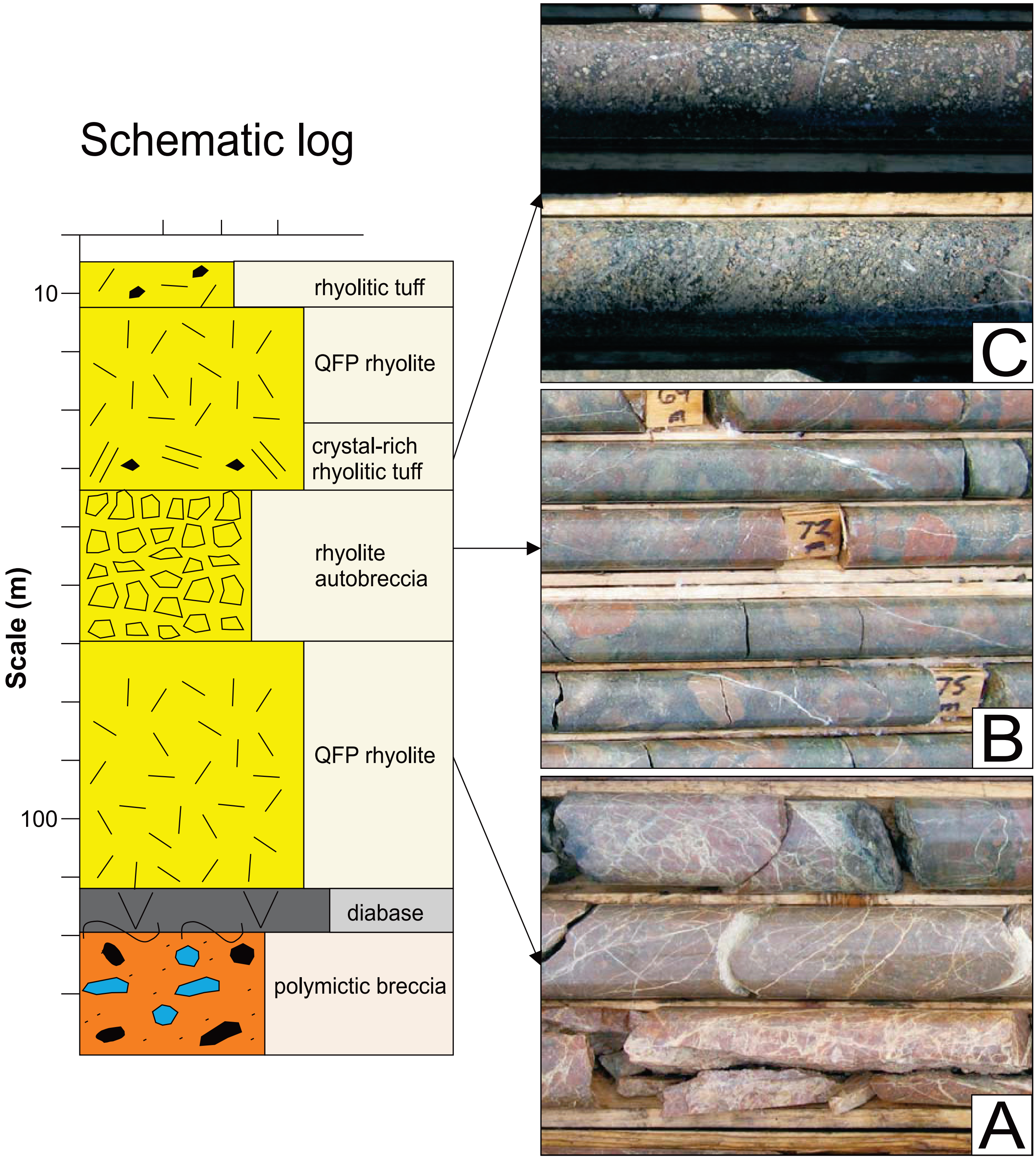


Figure 11. *Summary of the stratigraphic relationships of the rhyolite unit. Diameter of drillcore in all photographs is 4.76 cm. A) Quartz-feldspar porphyritic rhyolite cut by sericite-carbonate veins (H3396; 10 m). B) Autobrecciated rhyolite with characteristic fine-grained chlorite-altered matrix (H3378; 69 m). C) Rhyolitic, feldspar-rich tuff. The groundmass is altered to a fine-grained, dark chlorite (H3393; 88 m).*

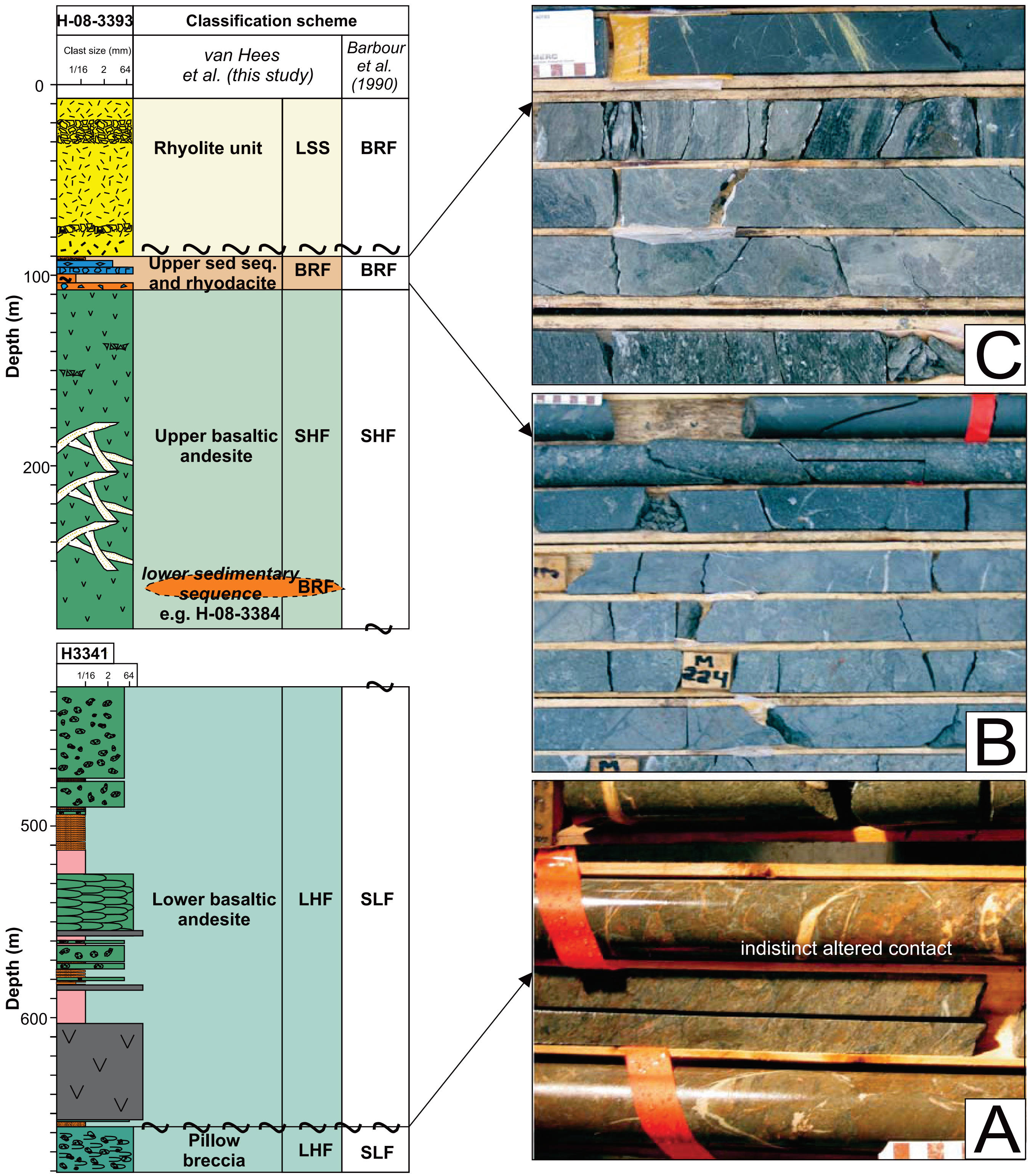


Figure 12. *Summary of the Lundberg Zone succession including photographs of the 3 observed major contacts. Diameter of all drillcore in photographs is 4.76 cm. A) Heavily altered contact between the lower and upper basaltic andesite (H3344; 1406 m). B) Conformable contact of the upper basaltic andesite and upper sedimentary sequence with rare rhyodacite clasts in a moderate, to poorly sorted sandstone matrix grading up to rhyodacitic breccia (H3388; 220 m). C) Diabase overlying sheared rhyodacite (H3396; 65 m).*

Thurlow and Swanson (1981) included it with the Lucky Strike ore horizon (Figure 4). This study demonstrates that the rhyolite unit is quartz-feldspar porphyritic, whereas structurally underlying felsic rocks of the Buchans River Formation are largely aphyric (Figure 12B, C). The observed contact, interpreted as a thrust fault, between the Buchans River Formation and overlying rhyolite, precludes the rhyolite being part of the Sandy Lake Formation, because an out-of-sequence thrust would be required to emplace young over old. In the classification of Thurlow and Swanson (1987) the rhyolite would have to be placed into the Lundberg Hill Formation. However, grouping of major mafic and felsic volcanic centres is undesirable under stratigraphic code. The simplest solution is to reserve the Lundberg Hill Formation for mafic rocks interbedded with chert and place quartz-phyric volcanic rocks in the herein proposed, Lucky Strike hanging-wall succession. The closest geographic feature to these rocks is the Lucky Strike open pit, which serves as a type-locality and gives it, its informal name. This informal name is appropriate until recognition of its original stratigraphic position is established to the west of Sandy Lake. Overall, the stratigraphy proposed by Thurlow and Swanson (1987) is supported by this study; the modifications proposed herein clarify the definition of the units allowing extrapolation to camp scale.

Correlation with other Deposits in the Buchans Mining Camp

The ores of the Buchans mining camp were classified as stockwork, *in situ* (*i.e.*, ~massive), or transported ore (*e.g.*, Jambor, 1987). The stockwork ore occurs exclusively adjacent to the Lucky Strike and Oriental orebodies. The Lundberg Zone mineralization is characterized by polymetallic stockwork, predominantly hosted in the Ski Hill Formation, and to a lesser extent the Buchans River Formation, and exhalative mineralization hosted exclusively in Buchans River Formation (*see* Figure 5). The stratigraphic setting of the stockwork is consistent with it being a peripheral zone to the Lucky Strike deposit. The exhalative mineralization correlates with both the North orebody and Lucky Strike, Rothermere, and Maclean ore horizons within the Buchans River Formation (*e.g.*, BRF: Figure 5).

The North orebody is the stratigraphically lowest orebody in the Buchans camp, occurring on a separate ore horizon from the other deposits at the base of the Buchans River Formation (Jambor, 1987) and correlates to the lowermost polymictic breccia of the upper sedimentary sequence at Lundberg (*e.g.*, Figure 5), although no *in situ* ore has yet been found on this horizon. The North orebody is overlain by siltstone and felsic tuff that form the footwall of the Two-level/Lucky Strike orebody and hosts the Rothermere and Maclean (Binney, 1987), and Clementine and Oriental orebodies (Thurlow and Swanson, 1981).

CONCLUSIONS

The Lundberg Zone is characterized by lateral continuity of stratigraphic units over the entire study area (800 by 500 m). The stratigraphic succession includes chert and basaltic andesite of the Lundberg Hill Formation, basaltic andesite of the Ski Hill Formation, felsic volcaniclastic rocks of the Buchans River Formation, and rhyolite of the newly proposed Lucky Strike hanging-wall succession. The observed stratigraphic relationships generally agree with earlier interpretations, but the recognition of distinct mafic and felsic units, including sulphide-bearing horizons, within the Buchans River and Ski Hill formations has important implications for exploration within the camp. In the Lundberg Zone, the Ski Hill Formation basaltic andesite hosts most of the polymetallic stockwork, and the Buchans River Formation volcaniclastic rocks host the exhalative mineralization and nearby Lucky Strike massive sulphides. The presence of sulphide clasts within a volcaniclastic lens in the Ski Hill Formation (lower sedimentary sequence) suggests that massive sulphide mineralization may not be limited to the traditional level in the Buchans River Formation and that multiple ore horizons may exist at depth.

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