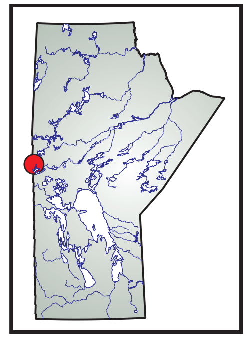
GS-8 Detailed (1:10 scale) mapping of regolith structure in dolerite below the Missi unconformity, Flin Flon area, Saskatchewan (part of NTS 63K12)

by M.G. Babechuk[1] and B.S. Kamber[1]



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Summary

The Paleoproterozoic Flin Flon Belt in the Trans-Hudson Orogen is host to a number of world-class regolith exposures, which formed during subaerial weathering at ca. 1.85 Ga. Paleosol is developed on exhumed arc-volcanic (1.90–1.88 Ga) and related successor-arc intrusive (1.87–1.84 Ga) rocks. The regolith is unconformably overlain by the syntectonic, ca. 1.85–1.84 Ga alluvial-fluvial deposits of the Missi Group. The Flin Flon paleosol is known internationally as being one of the first direct geological expressions for oxidative weathering conditions established after the Great Oxidation Event that occurred ca. 2.35 Ga ago. Surprisingly, there are no detailed, large-scale regolith maps available to date.

An initial survey of some of the best preserved regolith exposures was undertaken in the summer of 2010 to guide sampling for the purpose of high-precision geochemical analysis. The survey identified three high-quality outcrops for which large-scale maps and profiles were produced. This report presents a 1:10 scale grid-based geological map of the most spectacular regolith exposure, which developed on dolerite intrusions within mafic pillowed flows of the Louis formation. The map details the irregular development of hierarchical spheroidal weathering throughout the dolerite, as influenced by seafloor hydrothermal epidosite alteration zones within and at the contacts of the intrusions.

Introduction

Paleosols provide one of the best geological archives for the study of surficial conditions that persisted in the past at the ancient Earth's surface, due to their formation at the critical zone of interaction between the atmosphere, biosphere and hydrosphere. Weathering profiles develop as a function of the composition and internal structure of the parent material, the topography, the local climate and the duration of exposure. Such profiles record valuable information related to such topics as pH, the local rainfall and drainage conditions, and the oxidation state of the atmosphere (e.g., Rye and Holland, 1998; Retallack, 2001). In the absence of plants, soils are most strongly influenced by pH conditions, which are controlled by dissolved atmospheric (e.g., CO_2 and O_2) gases in surficial waters that penetrate the exposed rock surface (e.g., Rye and Holland, 1998; Sheldon, 2006). Geochemical characteristics of paleosols in the Flin Flon area are well known, for example the retention and oxidation of Fe (Holland et al., 1989), and the development of Ce anomalies (Pan and Stauffer, 2000), which indicate a transition from reducing to oxidizing atmospheric conditions by (at the latest) ca. 1.85 Ga. It is now generally accepted that the atmosphere had reached at least 1% of its present level of O_2 by ca. 2.35 Ga (Bekker et al., 2004), fundamentally changing the weathering conditions at the Earth's surface (e.g., through modification of the water pH, degree of oxidation and microbial biota). In addition to providing insight into the ancient atmosphere, weathering profiles may hold clues to mass balance between the soluble-element budget in the saprolite and the corresponding enrichment in the hydrosphere. For example, while the typical ratio of U/Th in most terrestrial igneous rocks is approximately 0.25, it may exceed 10 000 in modern river water and reach yet higher (>1E6) levels in modern oceans as a result of the greater solubility and flux of the mobile UO_2^{2+} into the hydrosphere during oxidative weathering (e.g., Asmerom and Jacobsen, 1993). Similarly, parameters such as U/Th in Precambrian paleosols may provide detailed information on elemental behaviour during ancient chemical weathering. The geochemical composition of paleosols may also be influenced by factors such as primary irregularities in the weathering profile, metamorphism, hydrothermal alteration and incomplete preservation. A complete understanding of these factors, and their influence on the geochemical trends of weathering profiles, requires detailed physical description and mapping of the structure of the regolith. The Flin Flon paleosols are exceptionally well-preserved despite the greenschist-facies metamorphic overprint, allowing study of both the physical and chemical surface conditions prevalent at ca. 1.85 Ga, a critical time in Earth's history.

Since the studies of Holland et al. (1989) and Pan and Stauffer (2000), the Flin Flon paleosols have not been re-examined and analyzed with the modern arsenal of geochemical tools available today, nor have they been mapped in sufficient detail to study their internal structure. Detailed mapping and high-precision geochemical analysis are thus combined in this study to obtain a comprehensive

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overview of the weathering environment. In an effort to better understand the changes in the weathering regime through part of the Precambrian, several of the best preserved Flin Flon paleosols were sampled and mapped in the summer of 2010. In order to evaluate the geochemical characteristics of ancient paleosols, it is first necessary to obtain an understanding of any original irregularities preserved in the weathering profile. Equipped with this knowledge, it is then possible to select the most suitable outcrops for sampling, specifically those where the weathering profile appears to be the least complex. Following this approach, the authors conducted detailed, 1:10 scale mapping and report here the results of their investigation of the regolith formed in a dolerite intrusion of the Louis formation below the Missi unconformity.

Regional Geology

The Paleoproterozoic Flin Flon greenstone belt is an amalgamation of several, 1.90–1.88 Ga (Stern et al., 1999; Rayner, 2010) tectono-stratigraphic assemblages that include juvenile ocean-floor back-arc rocks (Stern et al., 1995b), juvenile oceanic-arc rocks (e.g. Stern et al., 1995a; DeWolfe et al., 2009), ocean-island basalts and oceanic-plateau basalts (Stern et al., 1995b). The assemblages are now preserved as the 'Amisk Collage' — an intermediate-level crustal-scale tectonic stack forming the southeastern part of the Trans-Hudson Orogen, also known as the Reindeer Zone (Lucas et al., 1996). The most exhaustively studied assemblage is that composed of the juvenile oceanic-arc volcanic rocks, which contains world-class Cu-Zn volcanogenic massive sulphide (VMS) mineralization (Syme et al., 1999; Galley et al., 2007). Ore formation (i.e., the Flin Flon, 777 and Callinan deposits) is genetically linked to intra-arc rifting and associated with synvolcanic collapse structures (Syme and Bailes, 1993; Stern et al., 1999; Devine, 2003). The hangingwall formations (i.e., the Louis and Hidden formations; DeWolfe et al., 2009) to the ore deposits represent a resurgence of effusive volcanism.

In contrast to oceanic-arc volcanic rocks, the slightly older ocean-floor back-arc–basin basalts are not known to host economic mineral deposits. The various tectonostratigraphic assemblages were accreted between 1.88 and 1.87 Ga as a result of arc-arc collision(s) during ocean-basin closure, forming the 'Amisk Collage', and were stitched by successor-arc plutons (Ansdell and Kyser, 1992; Whalen et al., 1999) at ca. 1.87–1.84 Ga (not exceeding 1.838 Ga; Stern et al., 1999). Uplift as a result of crustal thickening, erosion and stabilization occurred coevally with deposition of successor-basin marine and continental sedimentary rocks between 1.87 and 1.84 Ga (Lucas et al., 1996). Deposition of volcaniclastic and epiclastic deposits of the Schist–Wekusko suite commenced by at least 1.87 Ga and extended to 1.85 Ga (Stern et al., 1999); subsequent turbidite sedimentation (Burntwood Group) was penecontemporaneous with deposition of the alluvial-fluvial Missi Group between 1.85 and 1.84 Ga (Ansdell et al., 1992; Heaman et al., 1992), the ages being constrained by U-Pb ages yielded by the youngest detrital zircons and crosscutting relationships. Prior to recent (post-1980) mapping, the collective oceanic-arc volcanic rocks and successor-arc sedimentary deposits were referred to as the Amisk Group and the Missi Group, respectively.

In the Flin Flon area, the Missi Group is characterized by conglomerate and sandstone units that rest unconformably on the juvenile-arc volcanic rocks and successor-arc plutons. The sedimentary units define two separate fining-upward sequences; each is marked by a basal conglomerate with a high clast/matrix ratio and succeeded by sandstone with significant hematite laminae (Stauffer, 1990; McNeill, 2007). This transition presumably represents a change from proximal fan-type deposits to more distal, braided stream-type deposits, but a detailed sedimentological study of the Missi Group remains to be done. At many locations of the basal Missi contact in the Flin Flon area, the underlying volcanic or plutonic rocks contain clear evidence of subaerial weathering, confirming that it is an unconformity (Holland et al., 1989; Stauffer, 1990; McNeill, 2007). The presence of features that are diagnostic of weathering, such as spheroidally-weathered corestones[2] with 'onion-skin' textures, confirms the authenticity of the Flin Flon paleosol. The most well-known exposure of the paleoweathering surface is that described in Holland et al. (1989), and subsequently by Pan and Stauffer (2000), located approximately 2.5 km southeast of the town of Flin Flon, along the Saskatchewan-Manitoba provincial border. At that location, the paleosol is developed on mafic, pillowed flows of the Hidden formation at an outlier of the Missi Group. This paleosol and the location of others in the Flin Flon area are shown in the simplified geological map of Figure GS-8-1.

Objectives of the study

In the summer of 2010, several of the paleosol localities in the Flin Flon area were visited as part of a comprehensive and on-going study that includes

[2] Corestone: broadly rectangular to spheroidal block of bedrock found typically in the lowermost saprolite and surrounded by progressively more weathered material. Weathering develops initially along cracks (e.g., joints) in the bedrock that form hydrological discontinuities of enhanced water-rock interaction. Weathering progresses along these hydrological pathways in a spheroidal pattern developing a progressively more rounded corestone with an outer shell complex and surrounding saprolite (e.g., see Ollier, 1967, 1971; Sarracino and Prasad, 1989; Patino et al., 2003; Fletcher et al., 2006; Røyne et al., 2008). In this report, the more general term 'regolith' is used in place of saprolite for the weathered bedrock surrounding the corestones.

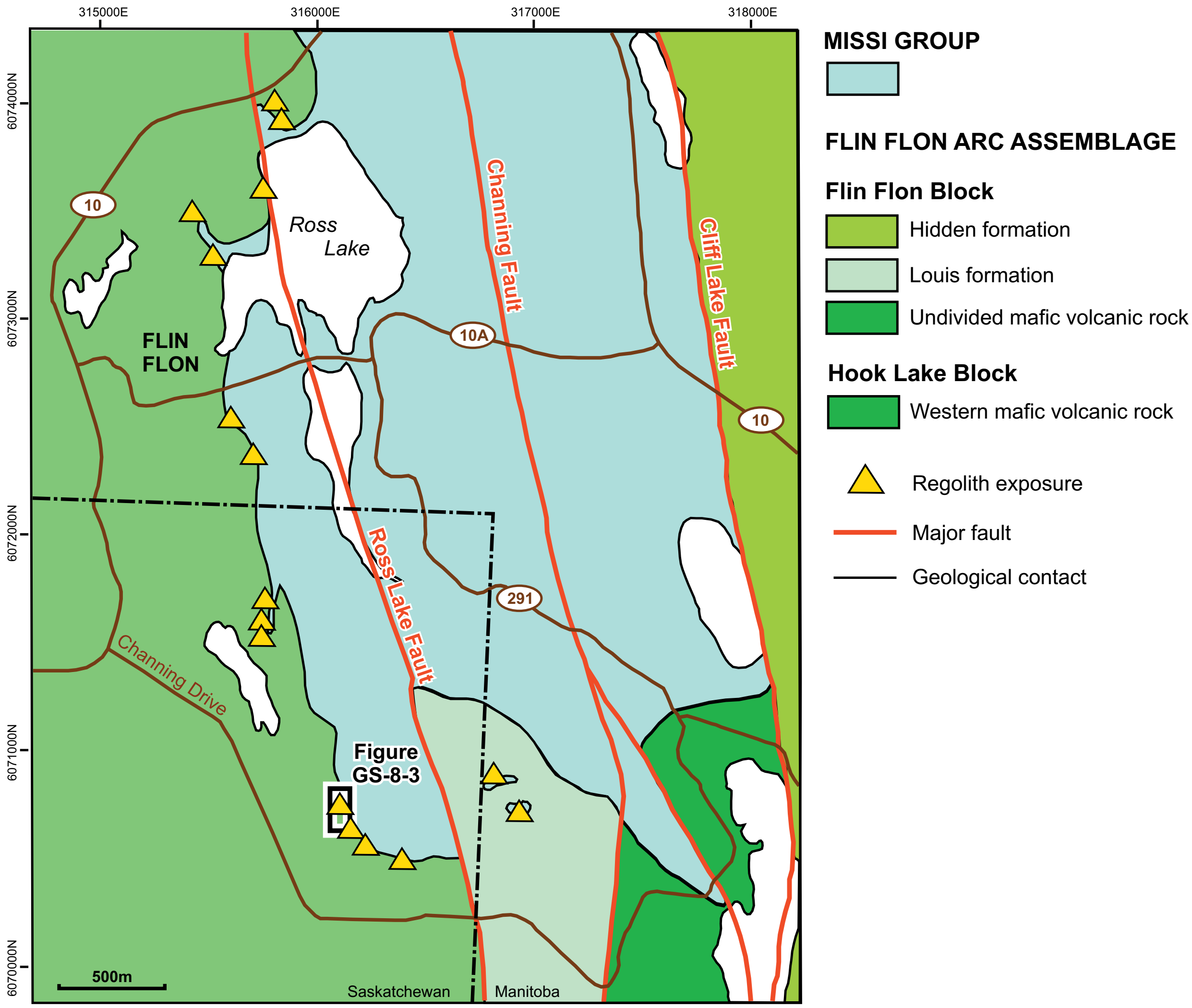

Figure GS-8-1: Simplified geological map of the Flin Flon area, based on Simard et al. (2010). Locations of paleosol exposures are as shown in Simard et al. (2010). The inset box denotes the approximate study area covered by the map in Figure GS-8-3.

- detailed, large-scale surveying of the paleoweathering surface and the Missi unconformity with emphasis on the regolith structure and development; and,
- sampling of complete paleosol profiles at different localities for petrography and high-precision geochemical analysis.

This report presents a 1:10 scale geological map of one of the best preserved regolith outcrops in the Flin Flon area, together with descriptions of the field methodology and map units, as well as preliminary observations and a geological interpretation.

Location and description of the outcrop

The outcrop in this study (inset in Figure GS-8-1) is located approximately 2 km south of the town of Flin Flon, just west of the Saskatchewan-Manitoba border. It is readily accessible via a short (< 0.5 km) northward hike from Channing Drive (Figure GS-8-1). The outcrop is remarkably well preserved, with only minor areas covered by vegetation or degraded by recent weathering and erosion. The topography of the outcrop reflects lithological changes, from the regolith (low-lying) to the more elevated dolerite and pillowed basalt (Figure GS-8-2).

Methodology

The outcrop in the study area was most recently mapped at a scale of 1:1000 by McNeill (2007), with a focus on the Missi Group conglomerate and sandstone in order to reconstruct the local paleodepositional environment. In the present study, detailed 1:10 scale mapping was conducted to investigate the unconformity contact, as well as the regolith structure and its development. The outcrop was mapped with the principal aims of

- evaluating the distribution of corestones; and
- tracing local variations of weathering intensity recorded by changes in the regolith.

Figure GS-8-2: *A view of the mapped outcrop looking north, approximately parallel to the surface trace of the unconformity contact. The author, shown for scale (height with extended arm: 2.1 m), is located approximately 9 m west of the unconformity (surface trace shown by dashed line) to demonstrate the topography of the mapped outcrop. At this scale, the Missi Group conglomerate can be distinguished from the dolerite and regolith based on its darker matrix colour.*

The field map was used to locate and document the most prospective areas for sampling a profile on the outcrop that records the progression from least-weathered dolerite to mature regolith. In addition, the map (with geological interpretation) will provide the contextual basis for the evaluation of geochemical data, when available.

Prior to deciding on the exact location and parameters of the map area, the outcrop was carefully studied to

- gain a basic understanding of the physical volcanology and contact relationships of rocks underlying the unconformity;
- identify mappable lithological units; and
- establish the most suitable areas for obtaining structural measurements and field photographs.

After the parameters of the map area had been established, an orthogonal grid, subdivided into 1 m^2 units, was superimposed on the outcrop. The orthogonal grid was oriented with the long axis approximately parallel to the strike of the unconformity and marked using chalk. At its maximum dimensions the grid, which contained 171 squares, was 28 m long and 9 m wide; certain areas on the grid were not mapped where continuous, non-weathered dolerite was present or outcrop was absent. A labelling system was applied to the individual 1 m^2 grid squares for reference. Having established a legend for the field map, mapping was completed in a single day by the two authors, starting from opposite corners of the grid, respectively. To conduct mapping, four squares, each measuring 10 cm^2, were outlined on separate sheets of letter-size paper and the map was developed by covering consecutive areas of 4 m^2. At the end of the day, all of the squares were cut out and taped together to produce the full, 1:10 scale map. A second, final day was used to revisit the very few areas of the map that did not match seamlessly, take field photographs and sample the regolith. Special care was taken to minimize the impact on the outcrop surface during sampling.

The original field manuscript of the map area was compiled and scanned; part of this map is shown in Figure GS-8-3 and the complete map, with visible resolution down to 5 cm of detail, is available for download as DRI2010005[3]. The original map was simplified and keyed with a legend of basic rock types for presentation in this report (Figure GS-8-3).

Rock types

Pillowed basalt

The lowest stratigraphic unit in the study area is pillowed basalt of the Louis formation. The Louis formation, together with the Hidden formation (DeWolfe and Gibson, 2006; DeWolfe et al., 2009), composes the hanging wall to the ore-hosting (i.e., Flin Flon, Callinan and 777 deposits) Flin Flon formation. The pillowed flows of the Louis formation in the study area are plagioclase- and pyroxene-phyric and also characterized by subrounded, quartz-filled amygdules. The basalt is dark grey on fresh surfaces and buff to brown on weathered surfaces. The Louis formation pillowed basalt is of little importance in the present work because the regolith, which is the main focus of this study, appears to have developed exclusively over the dolerite intrusion, located stratigraphically above the pillowed flows. A sample was taken from the core of a pillow immediately to the west of the mapped area (Figure GS-8-3) for comparison with the dolerite intrusions and regolith.

[3] MGS Data Repository Item DRI2010005, containing the data or other information sources used to compile this report, is available on-line to download free of charge at http://www2.gov.mb.ca/itm-cat/freedownloads.html, or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Innovation, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada.

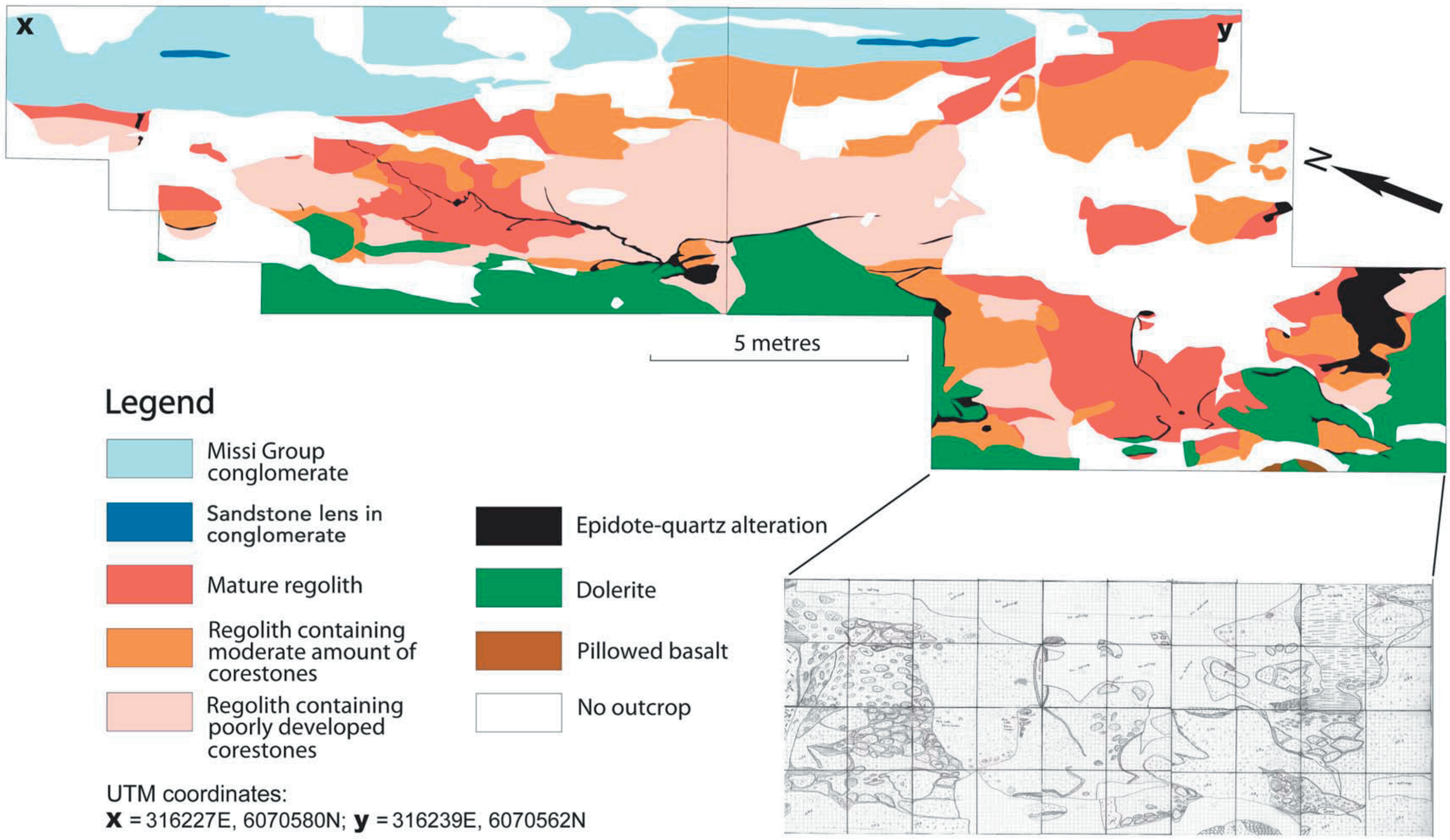

Figure GS-8-3: *Simplified geological map based on 1:10 scale mapping showing the regolith structure in dolerite below the Missi Group unconformity. The inset (bottom right) shows a portion of the original field map used to construct the simplified geological map. See text for a description of the map units.*

Intrusions

Geological maps of the study area (McNeill, 2007; Simard et al., 2010) show a mafic intrusion parallel to the Missi unconformity. McNeill (2007) describes the unit as "fine to medium grained, with 20–25% plagioclase phenocrysts". The intrusions are dark green to grey on fresh surface, but weather to a buff colour, like the pillowed basalt. In large outcrops surrounding the map area, it is possible to identify individual sills and determine their contacts with the pillowed flows and each other; based on these observations, the intrusion can be subdivided into three separate sill-like bodies. Within the detailed map area, subdivision of individual sills is thwarted due to the problem of projecting contacts through the regolith. The intrusion in direct contact with the Louis formation basalt to the west of the mapped area (Figure GS-8-3) is flow-banded with an irregular contact surface; it locally follows the topography of the pillowed flow surface, along which it intruded. On fresh surfaces, the dolerite is massive and contains no obvious internal structures or fabric, thus providing an ideal opportunity to study the hierarchical fracturing developed during spheroidal weathering (e.g., Røyne et al., 2008). Samples were obtained from the two largest, non-weathered dolerite intrusions, for the purpose of geochemical and petrographic comparisons between the intrusions, the pillowed flows and the various regolith types.

Epidote-quartz alteration zones

Epidote-quartz alteration, common in subaqueous basalt flows in VMS-hosting districts (e.g., Galley, 1993; Paradis et al., 1993; Banerjee et al., 2000), is due to high-temperature (~200–400^{o}C) hydrothermal fluid interaction. Pervasive epidote-quartz alteration is characteristic of mafic volcanic flows in much of the Flin Flon arc assemblage, including the Louis formation (Ames et al., 2002; DeWolfe et al., 2009). In the study area, pillowed basalt of the Louis formation is pervasively epidotized; the alteration is most intense in inter-pillow tuff. Epidote-quartz alteration is ubiquitous within the regolith and is manifested as irregular veins and localized amoeboid patches (DeWolfe et al., 2009), which appear to have exploited contacts between the doleritic intrusions (Figure GS-8-4d).

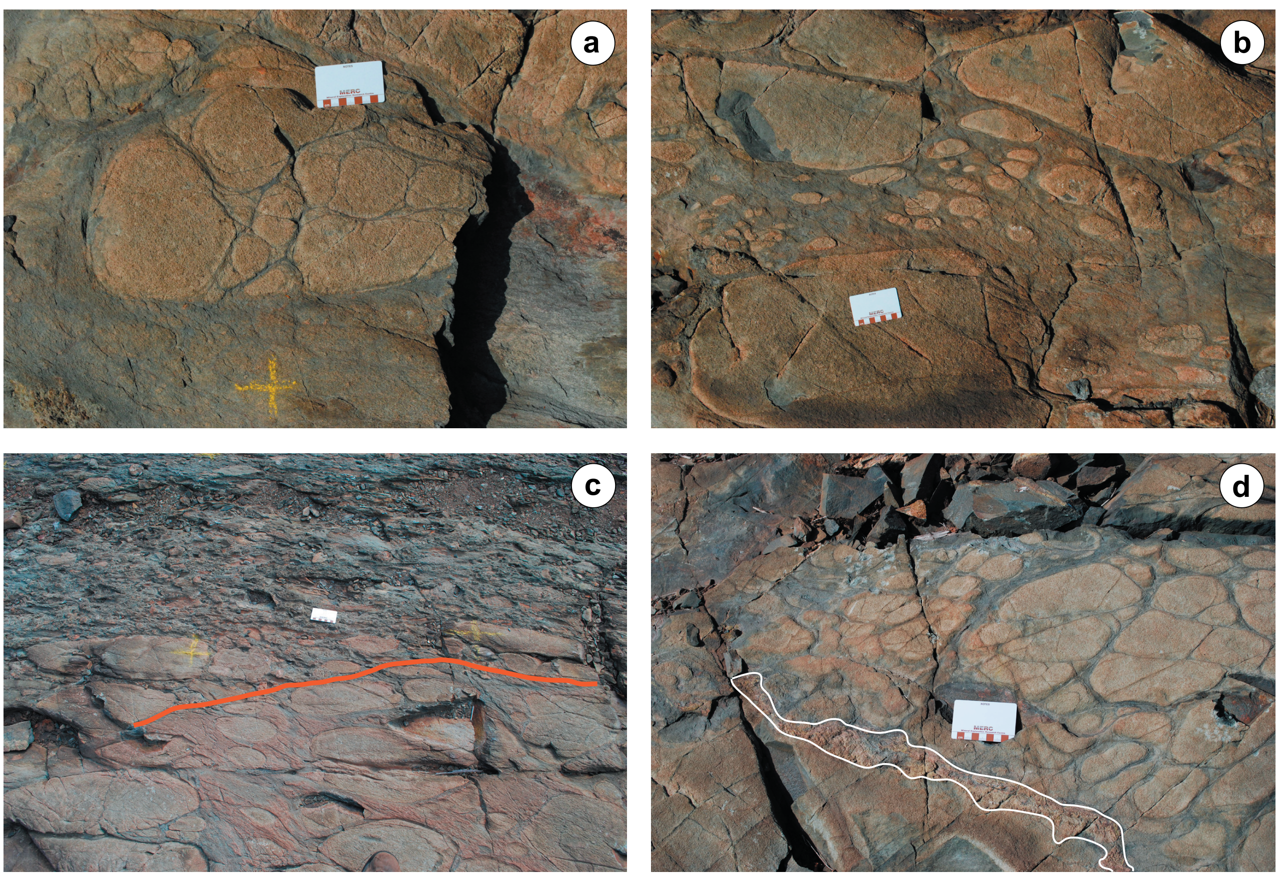

***Figure GS-8-4:** Field photographs of map area showing: **a)** corestone, surrounded by regolith, in the process of fracturing and forming smaller corestones (spheroidal weathering); **b)** small corestones in regolith in a zone surrounded by larger corestones; **c)** Missi unconformity, indicated by red line; note the presence of large, aligned dolerite clasts immediately above the contact and the darker matrix of the overlying basal conglomerate; **d)** epidote-quartz alteration vein (outlined in white) with relatively fresh, non-weathered dolerite below and abundant corestones (more weathered) above.*

Regolith

The regolith is distinguished from non-weathered dolerite on the outcrop surface by its darker, pale grey-green weathering colour. The amount of regolith above the dolerite typically increases as more surface area is exposed along weathering-induced fractures, eventually forming well-rounded corestones with 'onion-skin' textures. At the most advanced stage of weathering, the regolith becomes increasingly matrix-supported and develops into a chlorite-rich material with only sporadic, small corestones. This process, described as spheroidal weathering, is well-documented in modern or subrecent regolith profiles (e.g., Ollier, 1971; Fletcher et al., 2006; Buss et al., 2008). Dolerite in the study area demonstrates all stages of hierarchical fracturing and associated alteration during progressive spheroidal weathering (e.g., Figure GS-8-4a, b and d; Røyne et al., 2008). At the highest stratigraphic level of the regolith, the grey-green, chlorite-rich paleosol matrix changes to maroon, immediately below the Missi unconformity contact. This color change may represent either

- a paleoredox transition in the regolith; or
- exploitation of the unconformity contact by modern, oxidized surface waters.

Missi Group

Missi Group fluvial deposits immediately above the unconformity in the study area, which constitute the lower part of the Beaverdam Member of Stauffer (1990), were described and mapped most recently by McNeill (2007). The regolith is overlain by a laterally discontinuous, polymictic basal conglomerate. This conglomerate has a high clast/matrix ratio, with subrounded to subangular clasts ranging widely in size from <1 cm to 30 cm. The detailed analysis of the conglomerate by McNeill (2007) noted the presence of weathered dolerite and aphyric basalt corestones, as well as of clasts of quartz, amygdaloidal basalt and rhyolite, and siltstone. The abundance of weathered dolerite clasts decreases sharply toward the stratigraphic top of the conglomerate. Where the conglomerate contains abundant basaltic clasts, the contact with the regolith is identified by the relatively darker matrix of the conglomerate (Figure GS-8-4a) and the first appearance of non-doleritic clasts. Scouring of the conglomerate into the regolith is locally evident; elsewhere stratigraphic transition from regolith to conglomerate is indicated by lithological gradation between their respective matrices. The basal conglomerate contains thin (~50 cm), intercalated lenses of sandstone and is typically poorly sorted, clast-supported and lacks grading, consistent with a proximal alluvial-fan or braided-stream depositional environment (Stauffer, 1990).

The conglomerate/sandstone ratio is inversely proportional with stratigraphic level. The basal conglomerate, which is laterally discontinuous, is overlain by interbedded sandstone and conglomerate in an 'intermediate' unit that is locally in direct contact with the regolith at the northern and southern extremes of the unconformity exposure, within the study area (Stauffer, 1990; McNeill, 2007). At higher stratigraphic levels to the east of the map area, crossbedded and predominantly clast-free sandstone overlies the intermediate unit. The crossbedded sandstone is medium- to coarse-grained and contains conspicuous heavy mineral laminae (Stauffer, 1990).

Description of the map and discussion

Map units

The geological units described above were simplified in order to produce the geological map shown in Figure GS-8-3. The lowest stratigraphic unit, pillowed basalt of the Louis formation, is present at only one locality, near the south-western corner of the study area (Figure GS-8-3). The non-weathered dolerite intrusions were combined in a single map unit (dolerite), because individual sills could not be clearly traced through the regolith. In this study, the term 'regolith' was assigned to any part of the intrusions that showed evidence of weathering, ranging from development of incipient spheroidal weathering fractures to a pervasive, mature chlorite-rich paleosol matrix. The regolith was subdivided into three subunits: 1) areas of incipient weathering with large, minimally-fractured or poorly-developed corestones, 2) areas with an increasing proportion of regolith and moderate amounts of more advanced, spheroidally-weathered corestones, and 3) areas of mature regolith with few, if any, corestones and/or highly advanced ("ghost") corestones, as well as a large proportion of regolith matrix. Areas of epidosite that likely formed during seafloor alteration were mapped as a separate unit within the regolith and dolerite. Missi Group sedimentary rocks were mapped as a single unit, except for two lenses of sandstone within the basal conglomerate.

Regolith structure and the distribution of epidosite, spheroidal weathering and corestone development

At outcrop scale, the regolith under the Missi Group unconformity was not found to exhibit a systematic progression in weathering intensity between the unconformity and the unaltered dolerite, as shown by Figures GS-8-3 and GS-8-4. However, it is assumed that the weathering of the dolerite at ca. 1.85 Ga progressed in a style similar to that of modern regolith profiles (e.g., Buss et al., 2008), beginning with incipient fractures in the dolerite intrusion, which are then progressively chemically weathered along newly exposed surfaces (e.g., Buss et al., 2008; Røyne et al., 2008). Although spheroidal weathering has been widely documented, it is still poorly understood at a mineralogical, elemental and biological scale, even in modern profiles. A review of the topic is beyond the scope of this report; the sole focus of which is instead the macro-scale observations of corestones in the Flin Flon paleosols.

In the Flin Flon paleosol exposures documented on pillowed basalt, the distribution of corestones appears to be related to the original geometry of the pillows (Holland et al., 1989). The original weathering surface in this case would have been one of low relief and the more susceptible inter-pillow zones would likely have been exploited first during regolith development. In modern flood basalts, the progress of the alteration front is typically determined by the vesicularity of the rocks. The densest, least vesicular parts of flows are the most resistant to weathering and thus evolve as horizons, where large corestones develop rather than a mature regolith. Over time, where permeable zones occur below corestones, the rocks there become increasingly more weathered due to meteoric water that is funnelled down between the corestones (see Nesbitt and Markovics, 1997, Figure 1). However, the pattern of weathering intensity observed within the study area is irregular and apparently controlled by some additional factor. The distribution of corestones and the intensity of weathering appear to be at least partly related to the distribution of epidote-quartz alteration veins and patches. Intense corestone development is present above epidosite zones, in contrast to the dolerite immediately below, which suggests that these zones of seafloor alteration have played an important role due to their permeability and, ultimately, the extent of hydration during subaerial weathering (Figure GS-8-4d). This appears to have resulted in a discontinuous pattern of weathering intensity related to hydrological pathways created by the epidosite zones (Figure GS-8-3). The regolith mapped in this study is similar to that at the Flin Flon water tower locality, which is also developed on a mafic intrusion (Pan and Stauffer, 2000). The latter study noted, as in the present study area, the absence of a maroon weathering paleosol; this leads to speculation that it may have been removed prior to deposition of the Missi Group sediments. For the purpose of reconstructing a continuous weathering profile, future geochemical and mineralogical studies will have to take into account the distribution of corestones and epidote-quartz veins and zones of alteration.

The Missi unconformity

The geometry of the unconformity, as well as the nature of the sediments deposited onto the regolith, have important implications for future geochemical studies. The reason for this is that regolith formed on a steep topography is influenced by lateral element movement via both physical movement of the weathering profile downslope and, more importantly, transport in meteoric waters percolating downslope.

The unconformity between the regolith and the Missi Group sediments is inclined at a very low angle (less than 10°) to bedding in the overlying sedimentary rocks, as shown in Figure GS-8-3. At the eastern margin of the map area, the sedimentary rocks consist of conglomerate that is part of a discontinuous, approximately 50 m long and 4 m thick lens-shaped deposit (McNeill, 2007). Cross-bedded sandstone lenses within this conglomerate, which are in some cases located only 0.5 m from the unconformity, suggest that the conglomerate was deposited as a sheet or fan flow. These conglomeratic deposits, which are typically less than 1 m thick, are not characteristic of channel deposits. Sandstone above the basal conglomerate, located outside the map area, is interbedded with conglomerate and crossbedded, and was likely deposited in a braided stream that originated from a distal granitoid source (McNeill, 2007). The low angle of the unconformity and the nature of the conglomerate and the sandstone argue for a relatively subdued topography surrounding the map area. Consequently, the possibility exists that the vertical regolith profile, particularly below the larger corestones, may preserve systematic geochemical variation. At several locations along the unconformity, slight imbrication of corestones suggests that the regolith was disrupted by deposition of the conglomerate and that the uppermost part of the weathering profile may be missing. However, there is no evidence that a thick maroon regolith (likely more highly weathered), such as that found on nearby outcrops (e.g., Holland et al., 1989), had ever developed in this location.

Summary and Future Work

Previously, none of the Flin Flon paleosols have been mapped in sufficient detail to show their internal structure and demonstrate the progression of spheroidal weathering. In this report, a 1:10 scale geological map of one of the best preserved regolith outcrops in the Flin Flon area is presented. The corestone and regolith distribution at individual rock outcrops provide an excellent opportunity to examine hierarchical spheroidal weathering of Paleoproterozoic age. The size of corestones and the abundance of regolith do not change systematically towards the unconformity, as commonly observed in modern, well-drained and low-relief soils (e.g., Fletcher et al., 2006). Instead, pre-existing epidote-quartz alteration zones and veins within and between the dolerite intrusions appear to have been the principal factor controlling corestone distribution and regolith development during the period of subaerial weathering. The extent of removal of regolith detritus prior to deposition of the Missi Group is unknown. A summary of the inferred sequence of events described in this study is shown in Figure GS-8-5.

Geological sampling of the outcrop was undertaken following mapping. Two semi-continuous profiles were sampled through the areas of most extensive paleosol development. In 2010–2011, detailed mapping of this and a second, similar outcrop will be followed by high-precision geochemical analyses, as well as by petrographic

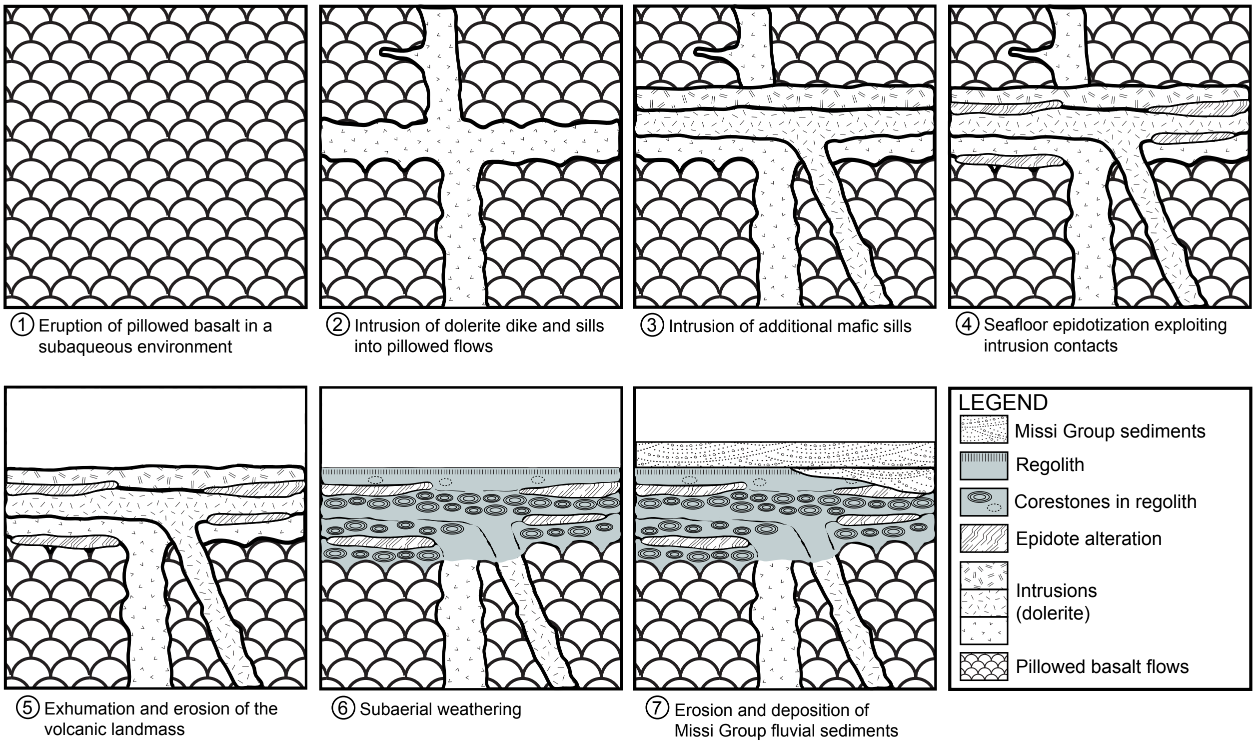

Figure GS-8-5: *Simplified schematic sequence of events in the development of regolith in the study area (also applicable to other Flin Flon paleosols). Note: in 4), the preferential hydrothermal alteration and epidosite formation along intrusive contacts; in 6), the irregular development of regolith between epidote alteration domains; and in 7), the scouring of Missi Group sediments into the upper part of the paleosol.*

and mineralogical investigations. It is anticipated that this work, in combination with the mapping, will yield further interpretations, as well as a better understanding of the paleohydrology and changes in the elemental budget during Paleoproterozoic subaerial weathering. The study of the Flin Flon paleosols will form an integral part of a larger project on Precambrian weathering profiles for a PhD dissertation by the first author.

Economic considerations

The first appearance of large tonnage, economic uranium deposits in the geological record is strongly linked to the redox geochemistry of uranium (see Cuney, 2010). The solubility of uranyl (U^{VI}) complexes in oxidized groundwater was only possible following the Great Oxidation Event (GOE; Bekker et al., 2004) at 2.35 Ga, paving the way for the formation of large uranium deposits, such as the Franceville basin deposits in Gabon (Gauthier-Lafaye and Weber, 1989), beginning in the Early Proterozoic. The exact timing at which the atmospheric oxygen fugacity reached sufficiently high levels to result in wholesale uranium mobility during oxidative weathering can be further refined with detailed geochemical studies of the Flin Flon and other Precambrian paleosols. Eventually, better understanding of the weathering behaviour of U through time can help focus exploration for sediment-hosted U deposits by eliminating those formed prior to active U mobility.

The weathering of Ni-rich rocks can, under favourable (typically tropical) climatic conditions, lead to the development of metal-rich laterite deposits. Laterites are temporally restricted to post-GOE times, with the oldest documented deposit at 2.2 Ga, near Sishen, South Africa (Gutzmer and Beukes, 1998). This is a consequence of the atmospheric (and climatic) conditions favouring the oxidation and retention of Fe and other metals in highly weathered rocks. In laterite deposits, elements like Ni are often associated with phyllosilicates (e.g., smectites) and Fe- and Mn-oxyhydroxides (e.g., Nahon et al., 1982; Yongue-Fouateu et al., 2006). Geochemical investigations of the regolith will help provide a better understanding of the behaviour of the transition metals (e.g., Ni, Cr, Co) in the weathering environment, including their physical distribution in less highly weathered rocks and in different mafic rock types.

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