Tertiary aluminium and nickel laterites in Western Australia, Germany and the United States of America

Open access explanatory notes of colour photographs, and petrographic and field notes compiled by:
Andreas Gerhard Mueller, 12a Belgrave Street, Maylands W.A. 6051, Australia. E-mail: andreasm@iinet.net.au

Updated November 2018

Contents

1. Technical aspects and copyright

The images stored in the three folders "Al-laterite200dpi", "Au-laterite200dpi" and "Ni-laterite200dpi" are high-quality JPEG-files saved with the embedded colour profile "Adobe RGB 1998". The Adobe colour space has a broader range than the older "sRGB IEC6-1966-2.1" profile more commonly used. The Microsoft and Apple operating systems allow selection of the colour profile for the display screen in the "System Preferences" under "Displays". The embedded colour of each photograph can be changed in Adobe Photoshop Creative Suite (CS) and in Adobe Photoshop Elements, computer programs available at most universities.

The author releases the images and these explanatory notes for teaching purposes at universities and other public institutions. The photographs are available as free downloads from the SGA website (e-sga.org). They are signed "AGM + year" by the author, who retains the copyright. The copyright cannot be transferred to a journal, publisher or any media organization without written consent. The photographs are intended to remain free-of-charge Open Access indefinitely. Acknowledgements should be made to the author and to the SGA website in the customary way. The text below has been carefully edited by the author but has not been reviewed independently.

2. Introduction

The colour photographs explained in the notes below illustrate laterite exposed in the open pits of various gold mines and in outcrops. They were taken during the past 30 years on occasion, and do not constitute a systematically assembled series. However, they will serve as an introduction to the subject. Bauxite, the product of laterite weathering, is the feedstock for alumina (Al_2O_3) refining and its smelting to aluminium, the principal lightweight industrial metal. Australia produced 30% of the world's bauxite in 2012, a total of 76 million metric tons (tonnes), and is second in alumina and fifth in aluminium production (data: Geoscience Australia). Gallium substitutes for aluminium in gibbsite, boehmite and diaspore and is recovered as a by-product, although the average content in bauxite is only 50 ppm (Jaskula 2011). Gallium is increasingly used in integrated circuits, flat panel displays, solar cells, and photo-detectors.

3. Laterite enriched in aluminium and nickel, Western Australia

The Yilgarn craton east of Perth rises 300-400 m above the coastal lowlands of the Perth sedimentary basin. The Archean bedrock consists of about 75% granite sensu lato, and of about 25% supracrustal greenstone belts (Fig. 1). The craton forms a morphological pene-plain covered by in-situ and re-deposited laterite of Tertiary age (Pidgeon et al. 2004), and by scattered clay-salt pans in ephemeral lakes. In many places, the laterite is eroded down to bedrock.

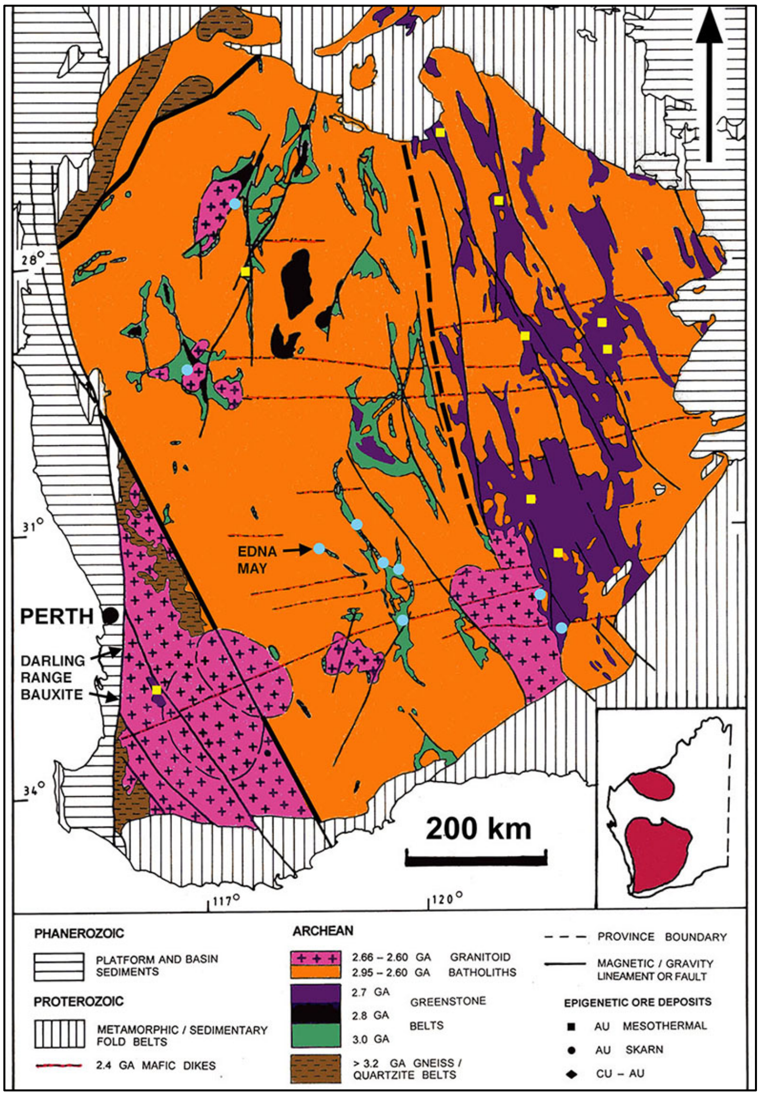


Fig. 1: Bedrock geological map of the Archean Yilgarn craton, Western Australia, showing the locations of the Darling Range bauxite and the Edna May gold deposit. Modified from Mueller and McNaughton (2000).

Bauxite composed of gibbsite, boehmite and diaspore (hydrous Al_2O_3) is mined on a large scale south of Perth in the Darling Range, where 50-70 m thick laterite overlies granites of the Darling Range batholith. Several large deposits (>500 million tonnes) are mined at grades of 27-30% Al_2O_3. Despite the low grades, the Darling Range accounts for 23% of global alumina production, as the bauxite has low reactive silica and is easy to refine. The deposits are described in Baker (1975) and in Owen and Hargreaves (1975).

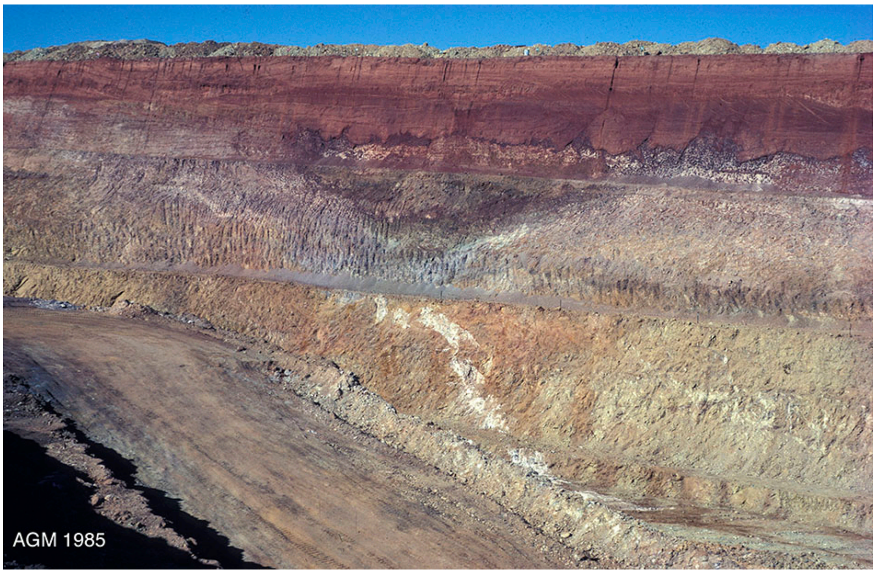
Saprolite overlying serpentinite and peridotite in the greenstone belts is currently mined at Murrin Murrin (total resource: 334 million tonnes at 0.99% Ni + 0.06% Co) in the Eastern Goldfields and near the town of Ravensthorpe (389 million tonnes at 0.62% Ni + 0.04% Co; Elias 2006). The Murrin Murrin open pits, operated by Minara Resources, produce ore containing up to 40,000 tonnes nickel and 5,000 tonnes cobalt per year. The smectite-rich ore (see Gaudin et al. 2005) is mixed with water to form slurry, which is fed into a High Pressure Acid Leach (HPAL) circuit. The geology of the Murrin Murrin and other deposits is reviewed in Elias (2006). The following photographs are in the **folder "Al-lateriteAUS"**:

Photograph Al-lateriteOraBanda (in situ): Slippery Gimlet open pit, August 1985, Ora Banda township, 65 km northwest of Kalgoorlie. The township is located at 30°23' south latitude and 121°03' east longitude on the Kalgoorlie (SH 51-9) 1:250,000 and Bardoc (3137) 1:100,000 map sheets. In-situ aluminium enriched laterite developed on tholeiitic meta-basalt: At the top are brown soil and dark brown iron-oxide pisolite duricrust, below is the mottled zone of cream-colored kaolin clay marked by numerous red-brown iron-oxide nodules and veins, in the foreground is the lower pallid zone of white kaolin clay which overlies green smectite-bearing saprolite on meta-basalt (both not exposed). The laterite is 40 m thick over unaltered meta-basalt but 80-120 m thick over parts of the Ora Banda gold lodes. Gold is variably depleted down to 45 m depth and enriched below in a 5-15 m thick zone above the saprolite-bedrock contact. The Ora Banda gold deposits are described in Harrison et al. (1990). Nickel-bearing laterite at Ora Banda, developed on ultramafic rocks, is described in Loftus-Hills (1975).

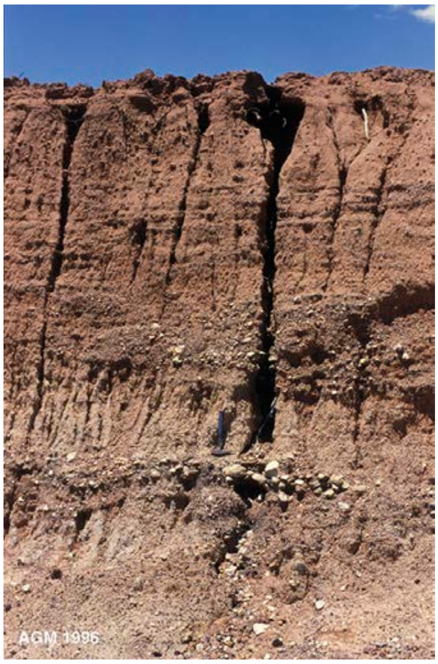
Photographs Al-lateriteCue1 to Cue3 (in situ): The gold mining town of Cue is located at the Great Northern highway 650 km NNE of Perth, at latitude 27°28' south and longitude 117°51' east. The laterite mesa shown (Cue1) is a prominent landmark 200 m east of the highway and about 1 km north of Cue town, photographed in July 1987. Remnant alumina-rich laterite rests on granodiorite-tonalite bedrock: The upper mottled zone was removed during Holocene erosion and the mesa now consists of white kaolin clay of the in-situ pallid zone, which is capped by a thick pisolite duricrust containing boulders of tonalite (Cue2 and Cue3, the pen is 14 cm long). The mesa rests on weathered saprolitic bedrock extending to a depth of 60-70 m below surface. The area between the mesa and Cue town contained extensive alluvial deposits of auriferous quartz derived from numerous quartz veins in sheared and altered granodiorite. Some of the thicker veins were mined underground from shallow shafts. Total production from the Cue field amounts to 345,343 tonnes of ore at 21.92 g/t gold (7,573 kg; Woodall 1990).

Photograph Al-lateritePerth (in situ): Close-up photograph of pisolite duricrust from in-situ laterite on granite, Darling Range, near the village of Kalamunda east of Perth. Most pisolites consist of a fragmental core and concentrically zoned red-brown iron oxide/hydroxide rims. Some are partly replaced by dark brown silica (conchoidal fracture). The pisolites are cemented by a hard but porous and vuggy matrix of grey opaline silica (opal + chalcedony), light brown limonitic kaolinite, and minor white kaolinite. The matchstick is 42 mm long.

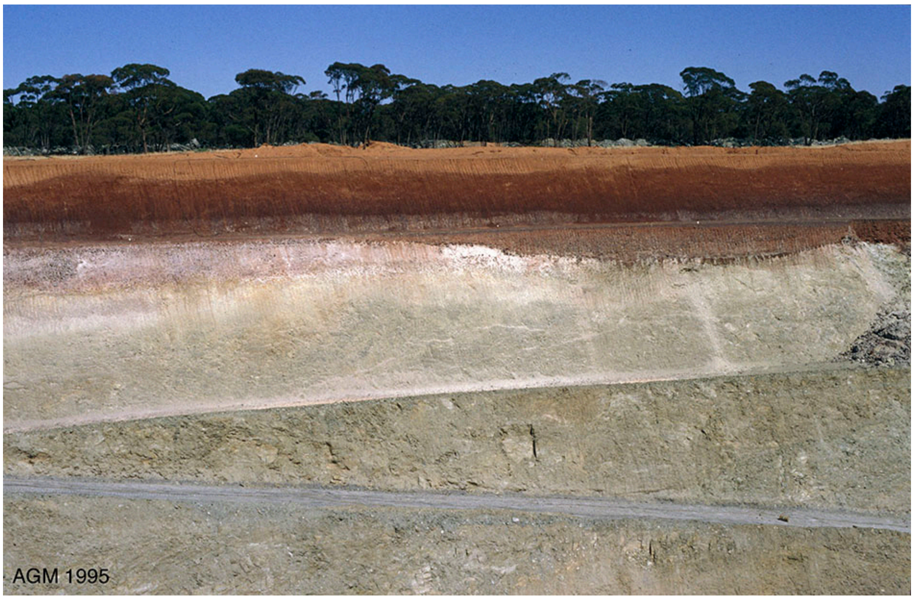
Photograph Al-lateriteSandKing (reworked): The Sand King gold mine is located 75 km NNW of Kalgoorlie, Western Australia, at 30°13' south latitude and 120°58' east longitude. The deposit is 2 km north of the historic town of Siberia shown on the Kalgoorlie (SH 51-9) 1:250,000 and Davyhurst (3037) 1:100,000 map sheets. The photograph shows the Sand King open pit in June 1985 looking southeast. Note the survey marks spaced 10 m apart at the rim of the pit. Partly eroded alumina enriched laterite developed on tholeiitic meta-basalt: The ferruginous and mottled zones have been removed by erosion. The top dark red layer now consists of wind-blown soil, alluvial gravels and aeolian sands, together about 15 m thick, marked by white chalcedony-magnesite nodules and calcrete at its base. Below the red layer is a 50 m wide and 20 m deep alluvial channel trending east, which is filled with ultramafic clasts but is barren of gold. The channel cuts into remnant mottled laterite, about 1-2 m thick, and into yellow-green saprolite developed in-situ on altered meta-basalt. The saprolite contains two thin layers of magnesite calcrete (former groundwater tables?). It is depleted in gold and, above the lodes, overlies a zone of semi-decomposed biotite alteration where pyrite is replaced by siderite. The Sand King gold deposit is described in Hill and Bird (1990).



Photograph Al-lateriteBurbidge1 and 2 (reworked): The Burbidge gold mining district is located in the Southern Cross greenstone belt, about 13 km SSE of Marvel Loch town, at latitude 31°32' south and longitude 119°34' east. The Tenaceous Pig open pit, where the photographs were taken in December 1996, is located about 1 km south of the main Great Victoria pit. The first photograph shows the vertical contact between graphitic paragneiss on the left and foliated skarn-banded amphibolite on the right looking south-southeast. The bench height is 20 m. The contact is occupied by a massive gossan composed of angular fragments of vein quartz and laminated chert cemented by brown goethite. The gossan replaces the sulphide-rich gold lode, and extends to the bottom of the pit. The pit wall on the right exposes iron oxide mottled laterite resting with irregular contact on grey-green smectite saprolite, which preserves the texture of the precursor amphibolite. A primary pallid kaolinite zone is absent. On the graphitic paragneiss, weathered to smectite-kaolinite saprolite, the mottled laterite terminates at shallower depth. The laterite is eroded and covered by dark red alluvial soil. Photograph Burbidge2 is taken looking east at a section through the soil. The hammer is 32 cm tall. The soil may be described as a poorly sorted fanglomerate composed of stratified pebble and boulder beds set in a matrix of dark red clay derived from iron oxide rich laterite. The clasts (1-20 cm) consist of white-grey granoblastic vein quartz, grey mica-bearing chert, and dark brown goethite-silica gossan. This assemblage suggests short-distance transport after erosion from local outcrops.



Photograph Al-lateriteCornish (reworked): The Cornishman open pit is located about 5 km SSE of the town of Southern Cross, east of the road to Marvel Loch, at 31°16' south latitude and 119°22' east longitude (Southern Cross 1:100,000 sheet SH2735). The photograph shows deeply eroded Tertiary laterite above ultramafic bedrock in the west at the wall of the open pit (March 1995). The full bench height is 10 m. The bedrock is green amphibole-chlorite rock (meta-komatiite) grading upwards into light green nickel-bearing smectite saprolite, which is overlain by mottled laterite composed of white kaolinite and red iron oxides. A broad channel of dark brown transported laterite (pisolitic, discordant contact) crosscuts the in-situ mottled one. Light brown wind-blown soil forms the top layer of the weathering profile.



Photographs Al-laterite, BauxiteAlbany15a and 15b: Bauxite from the Darling Range mines south of Perth, stockpiled in Albany harbour at the south coast of Western Australia, July 2015, ready for shipment to overseas smelters.

Photograph Ni-lateriteKanowna (in situ): Kanowna gold deposits, located about 20 km northeast of Kalgoorlie, Western Australia. Alunite Locality, an escarpment eroded down to a large pavement exposing saprolite bedrock at coordinates WGS 1984 UTM Zone 51J, 6617000 m north, 367570 m east. The photograph by Klaus Stedingk in 2006 shows the author looking at blue-green nickel enriched saprolite (smectite ± kaolinite) coated with limonite crusts. The bedrock is ultramafic amphibole-chlorite rock (meta-komatiite).

4. Laterite above the Edna May gold deposit, Western Australia

The Edna May gold deposit is located near the village of Westonia north of the Great Eastern highway about 55 km west of Southern Cross town, at latitude 31°18' south and longitude 118°41' east. The deposit is a case history for both the remobilization of gold and for the preservation of primary structures in laterite, as illustrated by the photographs assembled in the **folder "Au-lateriteAUS".**

The bedrock geology at Edna May is described in Mueller (1988) and in Drummond and Beilby (1990). The deposit occurs at the western termination of the Southern Cross greenstone belt in sheared and quartz-veined granodiorite gneiss, which strikes east and dips 45-50° north. The altered gneiss contains disseminated pyrite, pyrrhotite, molybdenite and scheelite, and averages about 0.5 g/t gold. It is underlain by altered amphibolite and overlain by ultramafic amphibole-chlorite rock. Thick horseshoe-shaped quartz ± microcline-biotite reefs mineralized with galena, chalcopyrite, scheelite and wolframite cut across the shear fabric (Fig. 2). They were selectively mined underground from 1911-1947 for a production of 0.564 million tonnes at 19.6 g/t recovered grade (11,044 kg Au).

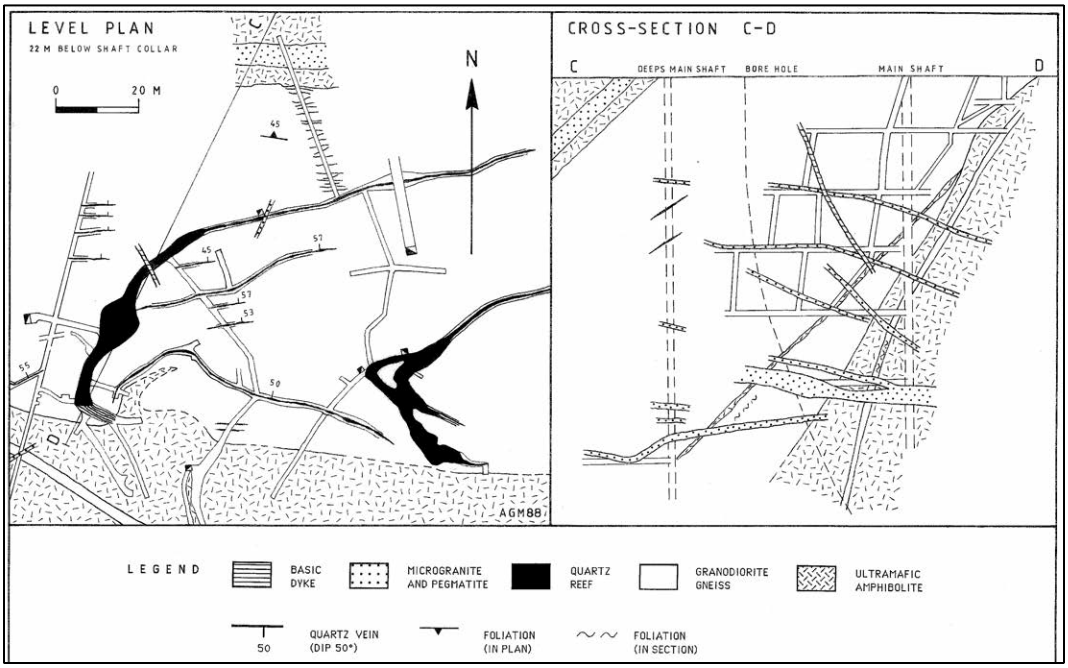


Fig. 2: Geologic map and cross section of the Edna May gold deposit, Yilgarn craton, Western Australia (Mueller 1988).

4.1. Edna May laterite zones

From 1986 to 1989, ore in laterite was mined amounting to 2.355 million tonnes at 2.30 g/t gold open-pit grade (5,323 kg Au recovered). In June 1989, an additional 2.5 million tonnes of low-grade stockpile ore at 1.3 g/t gold remained to be milled (Drummond and Beilby 1990). The standard laterite profile in Edna May gneiss based on pre-1985 drill core is summarized in Webster (1985, PhD thesis, the University of Western Australia):

0-2 m: Surface pisolites, loose rounded to sub-rounded iron-oxide pisolites and quartz-vein fragments.

2-5 m: Silcrete duricrust, hard layer of kaolin, pisolites and residual quartz cemented by abundant opaline silica.

5-12 m: Mottled zone, kaolinite stained with goethite-limonite and hematite-limonite nodules, minor jarosite and brecciated quartz-veins.

12-35 m: Pallid zone, cream-colored kaolinite, residual quartz and accessory sericite, little or no preservation of primary textures.

35-55 m: Saprolite or weathered gneiss composed of quartz, sericitized plagioclase, kaolinite, vermiculite, and rare alunite. Primary textures are preserved, and fractures are lined with goethite.

>55 m: Bedrock granodiorite gneiss composed of quartz, oligoclase-andesine, biotite, and hornblende.

The laterite profile at the mine developed and was modified during the following events (Drummond and Beilby 1990):

(1) Tertiary weathering of the gneiss, amphibolite, and ultramafic rocks to laterite and saprolite.
(2) Erosion of a broad but shallow north-trending channel filled with an upward fining fanglomerate termed "wash", composed of auriferous quartz boulders, grit, sand and mud.
(3) Continued laterite weathering during the Tertiary, mobilization and precipitation of iron leading to the formation of the surface pisolite zone and the iron oxide mottling of the "wash" and gneiss below.
(4) Holocene erosion of part of the laterite and deposition of transported soil, which is locally ore grade due to secondary gold enrichment. The soil is part of the pisolite resource.

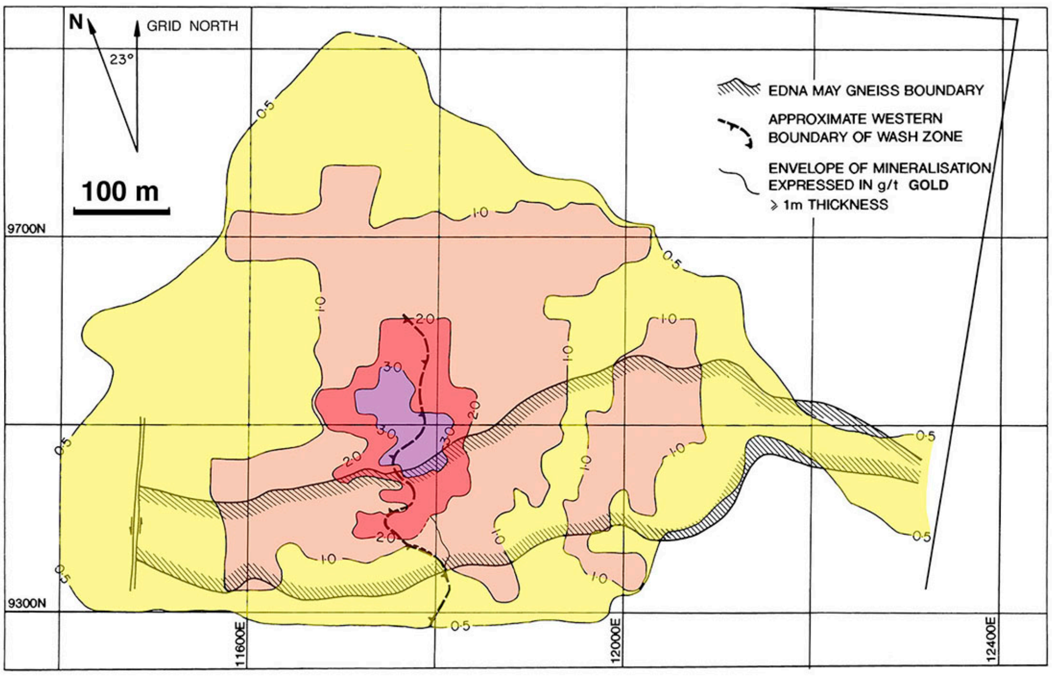


Fig. 3: Remobilized gold in the pisolite duricrust covering the Edna May gold deposit prior to open-pit mining, contoured in g/t gold at >1 m thickness. Modified from Drummond and Beilby (1990).

4.2. Auriferous pisolite duricrust

The surface iron-oxide pisolite layer is 1-5 m thick, and varies in composition according to the substrate. Over the footwall amphibolite, it is orange, porous, high in alumina and contains 0.1-0.5 g/t gold. Over the quartz boulder fanglomerate and in-situ gneiss, the layer is pink or orange, high in silica and low in iron, and contains 0.5-1.2 g/t gold. The duricrust consists of dark brown to purple-black pisolites in a tan matrix, both high in iron content, and contains 1.5-6.0 g/t gold where it overlies the hanging wall ultramafic amphibole-chlorite rock (Fig. 3). The top 1m-thick zone is poorly indurated and moderately auriferous, while the strongly indurated zone below (0.5-5 m) is strongly auriferous.

The process creating the auriferous duricrust involves the local groundwater, essentially saturated sodium chloride brine. Primary gold was dissolved and transported upwards as a chloride complex under the oxidizing conditions of laterite formation. It was then adsorbed onto iron hydroxide and oxide in pisolites (e.g. Webster 1985).

Photographs EdnaMayLaterite1 and 2: The author mapped and sampled the near-surface laterite on February 26, 1986 prior to open-pit mining. The photographs show a collapsed pre-1922 stope below the pisolite duricrust excavated in alluvial fanglomerate ("wash"). The stope is about 30 m east of the Edna May main shaft. The yellow scale is 2m tall. The duricrust layers are marked in blue paint. TOP LAYER, 0-1 m: Dark brown sub-rounded goethite pisolites 1-2 cm in diameter, closely packed, weakly indurated by interstitial red clay. Bulk sample (2 kg): 31 ppm Pb, 28 ppm As, 33 ppm W. MIDDLE LAYER, 1.0-1.4 m: Hard grey silcrete crust, opal, chalcedony and goethite cementing minor kaolin clay. Bulk sample (3 kg): 10 ppm Pb, 5 ppm As, 52 ppm W. BOTTOM LAYER, 1.4-2.8 m: Mottled brownish grey laterite, mainly white-grey kaolin moderately indurated by goethite-hematite and minor chalcedony. Bulk sample (1.9 kg): 15 ppm Pb, 12 ppm As, 181 ppm W. Local 1 cm vughs are lined with opal and chalcedony. An irregular network of fractures and joints up to 5 cm wide, filled with 5 mm brown pisolites, extends 70 cm into the mottled laterite. Angular fragments of auriferous reef quartz 2-10 cm long occur locally. These alluvial breccias were selectively mined in the stope.

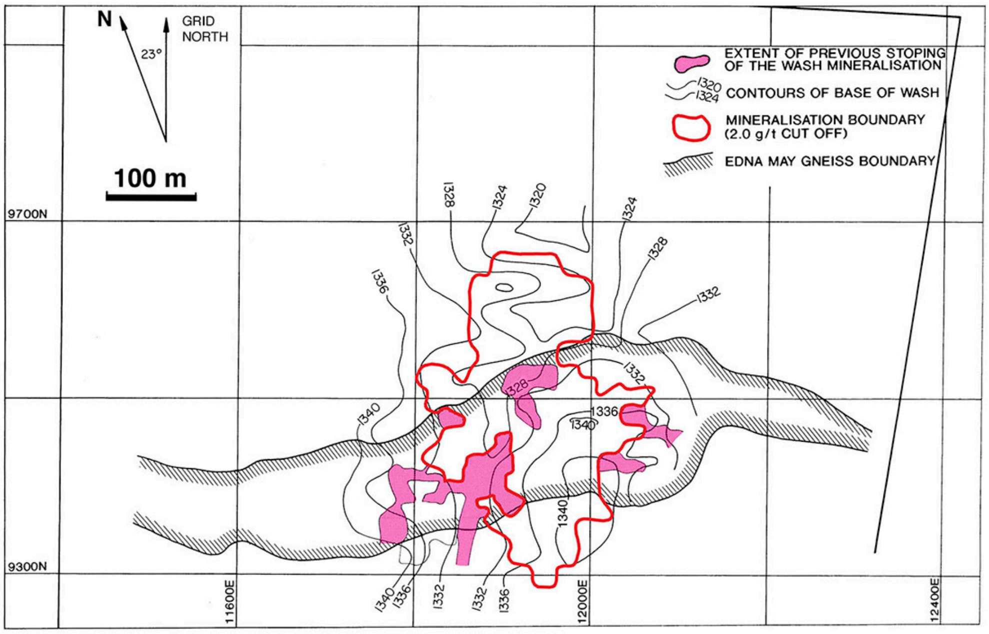


Fig. 4: Alluvial gold mineralization composed of auriferous quartz pebbles and boulders derived from the primary quartz reefs in Edna May gneiss. The clasts form lag deposits in poorly sorted fanglomerate filling a broad erosion channel (elevation contours in feet). Note the extent of stoping prior to 1922. Modified from Drummond and Beilby (1990).

4.3. Alluvial quartz-vein fanglomerate

The broad but shallow north-trending channel crossing the Edna May laterite was filled with an upward fining "wash", perhaps best described as a poorly sorted fanglomerate composed of auriferous quartz boulders, grit, sand and mud. This blanket of alluvial gold mineralization was partly stoped prior to 1922 (Fig. 4), and then removed during the subsequent open-pit operation. Gold grade correlated with the amount of auriferous quartz and with clast size (boulders up to 1 m long). Economic grades (>2.0 g/t gold over 1 m minimum thickness) were largely confined to alluvial lag deposits several meters thick at the base of the channel. Low grades of 0.3 g/t Au over 1 m persist down paleo-stream more than 1 km north of the Edna May gneiss.

4.4. Laterite in situ on Edna May gneiss

The in-situ laterite extends to an average depth of 55 m and comprises a pallid kaolinite and a saprolite zone (Drummond and Beilby 1990). In the pallid zone, the gneiss is completely weathered to soft white kaolinite containing minor granular quartz and quartz-vein fragments. Gold is depleted in the top 15-20 m of this zone and enriched below as indicated by the presence of visible foil gold. The saprolite zone is characterized by the incomplete weathering of micas and mafic minerals resulting in limonite-stained kaolin clay. The main high-grade quartz veins are preserved, and the soft rock between is evenly enriched to 1.0-1.4 g/t gold on average. The waste to ore ratio is 1:10 in this zone. Below the laterite is a deep zone of partial weathering to kaolinite and limonite with some gold enrichment and preservation of the gneiss fabric. This zone grades into sulphide-bearing, hard granodiorite gneiss averaging 0.3-0.5 g/t gold between the veins.

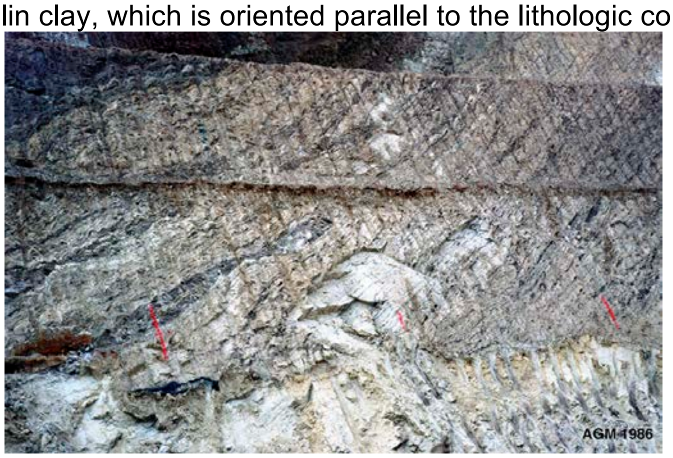
The author visited the Edna May mine a second time on June 16, 1987 when the open pit was 31-35 m deep. The photographs below illustrate the preservation of structures, especially quartz veins, in pallid-zone laterite and in saprolite.

Photograph EdnaMayLaterite3: Looking N40°W at the Westonia open pit north wall, the lowermost bench above the pit floor is 7 m high, the one above is 12 m high. The narrow assay trenches, spaced 5m apart, are in white kaolinite of the pallid zone on Edna May gneiss. The light green-grey saprolite in the far wall marks the hanging wall ultramafic rocks, crosscut by white kaolinized dikes and plugs of post-mineral granite. The contact gneiss-ultramafic rock is irregular in cross section and dips north. The low sub-bench close to the pit floor marks the location of photo 4. On the far left is weathered dark green footwall amphibolite.

Photograph EdnaMayLaterite4: Western part of the open pit (see photograph 3) north wall. Looking N20°W at quartz veins in kaolinized Edna May gneiss close to the contact with the hanging wall ultramafic rocks. A thin kaolinized granite dike cuts across the vein stockwork. The bench wall is 7 m high.

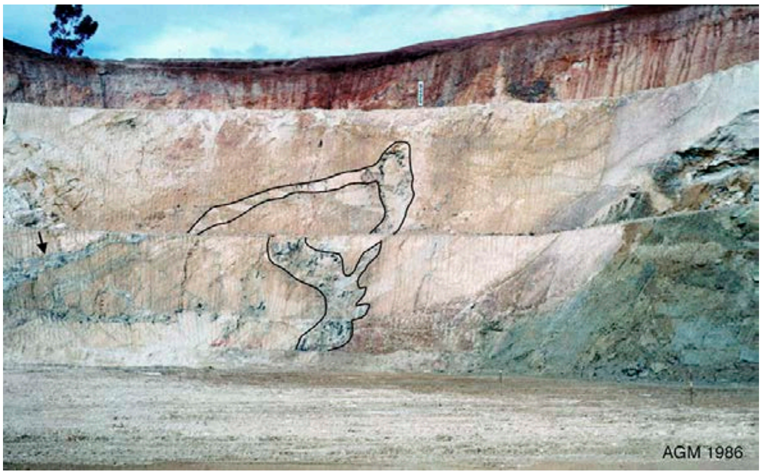
Photograph EdnaMayLaterite5: Looking north at the open-pit north wall, which exposes a section parallel strike of the contact of Edna May granodiorite gneiss with the hanging wall ultramafic rocks. In the open stopes on the right, auriferous quartz boulders were mined from alluvial lag deposits at the bottom of a broad channel. The two benches between the stopes and the pit floor are 12 m high. The assay trenches in the foreground, probably spaced 5 m apart, are in kaolinized Edna May gneiss. The hanging-wall contact is undulating. The gneiss at the contact is marked by a strong foliation defined by parallel quartz veins in white laterite. A flatly dipping kaolinized granite dike occurs in the ultramafic rocks. Photos 6 and 7 are close-ups of the gneiss in the lowermost pit bench, close to the HW-contact.

Photograph EdnaMayLaterite6: Looking N50°E at the north wall of the open pit, lowermost bench. The red paint marks are 5 m apart. The hanging wall ultramafic rocks, weathered to saprolite, are in the upper left corner of the photograph. Close to the contact, the Edna May gneiss contains quartz stringers and thick boudinaged veins defining a strong structural fabric in limonitic kaolin clay, which is oriented parallel to the lithologic contact.



Photograph EdnaMayLaterite7: Looking N40°E at the north wall of the open pit, lowermost bench. The part of the bench in the photograph is about 6 m high. Branching auriferous quartz veins (QTZ) sub-parallel to foliation in Edna May gneiss, which is weathered to light brown limonitic kaolin clay, are crosscut by a flat micro-granite dike (bottom of bench) and by irregular pegmatite dikes (red paint crosses), both also weathered to white kaolinite. The micro-granite grades into and contains schlieren of pegmatite.

Photograph EdnaMayLaterite8: Looking ESE (N115°E) at the east wall of the open pit from the pit floor. The two benches are each 6 m high. The photograph shows a cross section through the folded Consolidated quartz reef, about 1 m thick in the fold limb on the left, which is stoped and backfilled in the fold nose. The reef terminates at the north-dipping contact with footwall amphibolite, weathered to mottled grey laterite and green saprolite. The Edna May gneiss is weathered to pale yellow-brown limonitic kaolinite. The reef nose cuts across the foliation defined by quartz stringers on the left, which are parallel to the limb of the reef. Remnant reef quartz and the stopes, filled with white quartz sand and blackened timber, are outlined in black illustrating the shape of the Consolidated structure. The black arrow indicates the unmined part of the quartz reef.



Photograph EdnaMayLaterite9: Looking ESE (N120°E) at the east wall of the open pit, lowermost bench. The part of the bench in view is about 5 m high. Close-up view of weathered Edna May gneiss below the fold nose of the Consolidated Reef. A quartz vein is folded by movements on the principal foliation planes, which are sub-parallel to the lithologic contacts and marked by quartz stringers dipping to the left.


AGM 1986

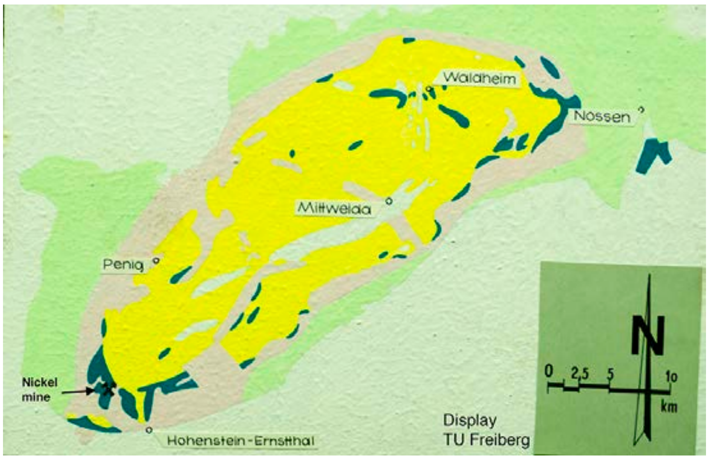
5. Tertiary nickel saprolite in Saxony, Germany

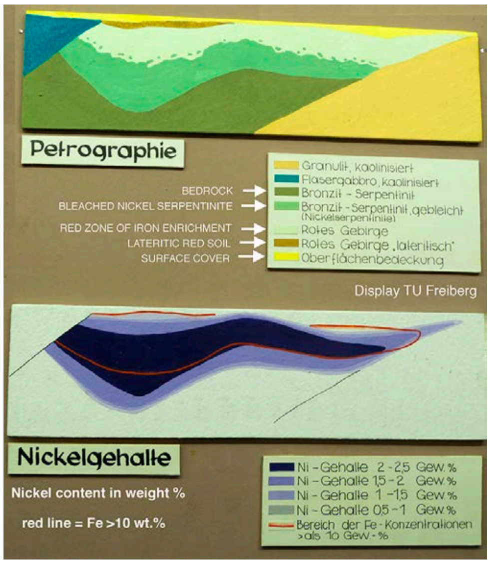
The classic nickel "laterite" deposits on the Pacific island of New Caledonia, which overlie serpentinite and peridotite in an obducted ophiolite complex, have been in continuous production since the late 19th century but still contain about 10% of the world's nickel reserves (in 2010, Geoscience Australia). Although the product of laterite weathering under tropical conditions, the nickel ore is concentrated in the saprolite zone above bedrock.

In central Europe, a humid climate prevailed during the Eocene and laterite weathering during this time accounts for at least some of the kaolin clay deposits in Paleozoic granite mined in Austria, the Czech Republic, and Germany (Höhn et al. 2014). On ultramafic rocks, Tertiary weathering led to the formation of nickel saprolite mined at Callenberg south of the village of Glauchau in Saxony, Germany. Photographs from this deposit are explained below and are stored in the **folder "Ni-lateriteGER.USA".** They were taken in July 2014 in the Ore Deposit Collection of the Technical University of Freiberg, Saxony, Germany, with the kind permission of curator Christin Kehrer.

A deposit similar to Callenberg occurs near Frankenstein (Ząbkowice Śląskie, 50°35' north, 16°49' east) in Silesia, southwest Poland. Concise descriptions of the Frankenstein (production: 2,500 tonnes nickel) and New Caledonian deposits from Beyschlag, Vogt and Krusch (1916) are inserted below after the references.

Photograph Ni-LateriteSaxony1: Simplified geologic map showing the Paleozoic Saxon Granulite Dome (yellow), its inner rim of mica schist and gneiss (pink), and its outer rim of low-grade metamorphic phyllite (pale green). Meta-gabbros and serpentinites, the latter constituting the substrate of Tertiary nickel saprolite, are shown in dark green-blue.
Photograph Ni-LateriteSaxony2: Schematic sections of a nickel hydrosilicate deposit formed during Tertiary laterite weathering at the southern margin of the Paleozoic Saxon Granulite Dome. Upper section: lithology, lower section: nickel content in weight percent. The Holocene cover is shown in yellow (Oberflächenbedeckung). The German term "Rotes Gebirge" (upper section) is applied to red soil and to saprolite marked by more than 10 wt.% iron content (outlined red in the lower section).





Photograph Ni-LateriteSaxony3: Callenberg nickel hydrosilicate deposit at the southern margin of the Paleozoic Saxon Granulite Dome, Saxony, Germany. Garnierite replaces serpentinite and is covered by minor black manganese oxide crusts.
Photograph Ni-LateriteSaxony4: Callenberg nickel hydrosilicate deposit at the southern margin of the Paleozoic Saxon Granulite Dome, Saxony, Germany. Garnierite, partly colloform, replaces serpentine pseudomorph after coarse bronzite crystals (?).

Photograph Ni-LateriteSaxony5: Callenberg nickel hydrosilicate deposit at the southern margin of the Paleozoic Saxon Granulite Dome, Saxony, Germany. Epoxy-backed section showing garnierite replacement in serpentinite, the panel is 40 cm wide.

6. Tertiary nickel saprolite in Oregon, U.S.A.

The Nickel Mountain mine is located near the small town of Riddle in Douglas county, southwest Oregon, United States of America. Though small amounts of ore were mined in the late 19th century, large-scale open-pit operations began in 1954 resulting in the production of 7.12 million metric tons of ore at 1.50% Ni until 1964 (84,503 t Ni, recovery = 79-80%), when the mine had about 16 years of reserves (Cumberlidge and Chace 1968). The deposit consists of Tertiary red topsoil, saprolite, and garnierite-chalcedony boxwork developed on Upper Jurassic peridotite and lesser serpentinite of the Klamath Mountain terrane, which extends from northern California into Oregon. Fresh peridotite and serpentinite contain 0.29-0.52 % NiO but only 0.01-0.02 % CoO. The mill-head grade thus indicates a three-fold enrichment of nickel in the saprolite zone (Cumberlidge and Chace 1968). Four hand specimens from the Nickel Mountain mine, stored in the Ore Deposit collection at Stanford University, California, were photographed in 1993. The collection is now part of the University of Reno, Nevada.

Photograph Ni-lateriteRiddle254: Sample OD-32254, box-work ore from the Nickel Mountain mine, Riddle, Oregon. Pale green to blue-green garnierite replaces massive serpentinite. A network of light brown chalcedony veinlets (20 vol.%, 0.2-3 mm, hard>steel) enclosing garnierite-serpentine aggregates (moderate hardness, soft<steel) defines the box-work texture. The specimen is locally magnetic and contains fine-grained (0.1-0.5 mm) black oxides, perhaps chromite + magnetite. Carbonate (tested 15% HCl) and fluorescent minerals are absent. The matchstick is 3 cm long.

Photograph Ni-lateriteRiddle212: Sample OD-45212, sepiolite ore from the Nickel Mountain mine, Riddle, Oregon, collected in 1967. Massive white clay (soft<<steel), reacting elastic when scratched with the fingernail, is mixed with streaks of accessory light green smectite (? shrinkage cracks). The sepiolite encloses lenses of limonitic leached serpentinite. Carbonate is absent (tested 15% HCl), and the specimen is non-fluorescent under hard ultraviolet light. Sepiolite has a fibrous structure, and is a member of the palygorskite group of clay minerals. At Nickel Mountain, sepiolite is a minor ore mineral filling veins along fault planes. The US dime is 18 mm across.

Photograph Ni-lateriteRiddle214: Sample OD-45214, box-work ore from the Nickel Mountain mine, Riddle, Oregon, collected in 1967. Veins filled with a dark blue-green mineral (soft<steel, Ni-chlorite or clay?) and with colloform light green garnierite (hard>steel) form a network in leached limonitic serpentinite, which is locally weakly magnetic. Botroidal colloform surfaces indicate open-space filling. Carbonate is absent (tested 15% HCl), and the specimen is non-fluorescent. The US dime is 18 mm across.

Photograph Ni-lateriteRiddle216: Sample OD-45216, box-work ore from the Nickel Mountain mine, Riddle, Oregon, collected in 1967. Ochre-brown leached serpentinite or weathered peridotite (soft<steel) lined by a dense network of thin (0.1-0.5 mm) chalcedony veinlets, which enclose limonitic serpentine-iddingsite (?) aggregates (3-5 mm). Thicker veins (3-15 mm) are banded and vuggy, and consist of light brown chalcedony (hard>steel) and pale green garnierite. Carbonate is absent (tested 15% HCl). The rock is porous and rapidly absorbs the acid, non-magnetic, and non-fluorescent. The US dime is 18 mm across.

7. References

Mineralium Deposita Thematic Issue on Supergene ore deposits (2017, vol. 52, no. 7), edited by B. Orberger and M. Cathelineau: Articles on nickel laterite and bauxite deposits.

Baker GFU (1975) Darling Range bauxite deposits, W.A. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 5, pp 980-986

Beyschlag F, Vogt JHL, Krusch P (1916) The deposits of the useful minerals and rocks: Origin, form and content, Volume 2 (translated: Tuscott SJ). MacMillan & Co. Ltd., London, pp 950-965

Cumberlidge JT, Chace FM (1968) Geology of the Nickel Mountain mine, Riddle, Oregon. In: Ridge, JD (ed.) Ore Deposits of the United States, Graton-Sales Volume 2, pp 1650-1672. The American Institute of Mining, metallurgical, and Petroleum Engineers Inc., New York.

Drummond AJ, Beilby GR (1990) Westonia gold deposits. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 14, pp 289-295

Elias M (2006) Lateritic nickel mineralization of the Yilgarn Craton. SEG Special Publication no. 13, pp 195-210

Gaudin A et al. (2005) Clay mineralogy of the nickel laterite ore developed from serpentinized peridotites at Murrin Murrin, Western Australia. Australian J Earth Sci 52: 231

Gaudin A et al. (2004) Accurate crystal chemistry of ferric smectites from the lateritic nickel ore of Murrin Murrin (Western Australia). I. XRD and multi-scale chemical approaches. Clay Minerals 39: 301

Gleeson SA, Butt CRM, Elias M (2003) Nickel laterites: a review. SEG Newsletter no. 54, p. 1 and 12-18

Harrison N, Bailey A, Shaw JD, Petersen GN, Allen CA (1990) Ora Banda gold deposits. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 14, pp 389-394

Hill BD, Bird P (1990) Sand King gold deposit. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 14, pp. 377-381

Höhn S, Frimmel HE, Pašava J (2014) The rare earth element potential of kaolin deposits in the Bohemian Massif (Czech Republic, Austria). Mineralium Deposita 49: 967-986

Jaskula BW (2011) Gallium: U.S. Geological Survey Mineral Commodity Summary, pp 58-59, online at: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/index.html#mcs

Loftus-Hills GD (1975) Ora Banda lateritic nickel deposits, W.A. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 5, pp 1010-1011

Mueller AG (1988) Archaean gold-silver deposits with prominent calc-silicate alteration in the Southern Cross greenstone belt, Western Australia: Analogues of Phanerozoic skarn deposits. Geology Department & University Extension, the University of Western Australia, Publication no. 12, pp 141-163

Mueller AG, McNaughton NJ (2000) U-Pb ages constraining batholith emplacement, contact metamorphism, and the formation of gold and W-Mo skarns in the Southern Cross area, Yilgarn craton, Western Australia. Economic Geology 95: 1231-1257

Owen HB, Hargreaves MR (1975) Mount Saddleback bauxite area, W.A. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 5, pp 987-991

Pidgeon RT et al. (2004) Late Miocene $(U+Th)_4He$ ages of ferruginous nodules from lateritic duricrust, Darling Range, Western Australia. Australian J Earth Sci 51: 901

Woodall R (1990) Gold in Australia. Australasian Institute Mining Metallurgy, Melbourne, Monograph no. 14, pp. 45-67

8. Nickel saprolites in Beyschlag, Vogt and Krusch (1916)

In 2003, nickel laterites accounted for about 40% of the annual world nickel production, and for about 60% of the land-based resources containing >1% nickel (Gleeson et al. 2003). Summaries of the geology of the New Caledonia and Frankenstein (Silesia) nickel laterite deposits are scanned from the textbook: Beyschlag, Vogt and Krusch (1916) The deposits of the useful minerals and rocks: Origin, form and content, Volume 2. MacMillan Co. Ltd., London. Remarks on early mining at Riddle, Oregon, are on the last page.

THE NICKEL-SILICATE, OR GARNIERITE DEPOSITS

LITERATURE

H. B. v. Foullon. 'Über einige Nickelvorkommen,' Jahrb. d. k. k. geol. Reichsanst. XLIII., 1892.

Lodes and veins of nickel-magnesium hydrosilicates are found all over the world under practically the same conditions, in more or less serpentinized olivine rocks, and exceptionally also in associated augite rocks. Such deposits occur very extensively on the island of New Caledonia, where they are of great economic importance. Similar occurrences are those at Frankenstein in Silesia, Riddles in Oregon, Webster in North Carolina, and Revda in the Urals. The occurrence at Malaga in Spain, already described,[1] which extends below the ground-water level, occupies a place by itself.

Of the mostly light-green nickel silicates characteristic of this group, garnierite—so named after Jules Garnier the discoverer of the New Caledonian ore; or numeite, after Numea the capital of New Caledonia—having a specific gravity about 2·9, is the most frequent. The composition of this mineral is approximately $H_2(Mg, Ni)SiO_4$, with variable amounts of NiO and MgO. Some samples have given as much as 45 per cent of NiO,[2] though the average content of the clean mineral is only 15–25 per cent. In addition, genthite, which is very similar to garnierite, nickel-gymnite, revdanskite, pimelite, schuchardite, etc., are worthy of mention. All these minerals are amorphous or cryptocrystalline, and usually badly defined as mineral species. The so-called nickel-chocolate—a chocolate-coloured ore of somewhat variable composition, and obviously consisting of a mixture of different minerals—also occurs very extensively in New Caledonia. At Frankenstein,[3] the so-called 'grey ore,' a somewhat decomposed serpentine containing a few per cent of nickel, occurs in large amount. In New Caledonia, at Revda, and at other places, the nickel-silicate deposits are accompanied by separate deposits of asbolane, that is, cobalt-manganese ore, the two classes of deposit being, however, always distinctly separated from each other.

The composition of these ores may be gathered from the following analyses taken from works afterwards cited :

[1] *Ante*, p. 299. [2] Analyses, No. 1*a*–1*c*. [3] *Postea*, p. 961.

[Table

	New Caledonia.							Riddles.	Revda.
	Garnierite.			Chocolate Ore.		Meer-schaum.	Export Ore.		
	1*a*.	1*b*.	1*c*.	2*a*.	2*b*.	3.	4.	5.	6.
SiO_2	35·45	37·49	42·61	33·70	37·05	41·80	42	48·82	54·15
Al_2O_3 }				1·40	0·63	...	1	...	0·23
Fe_2O_3 }	0·50	0·11	0·89	19·09	16·92	1·26(1)	15	0·06	0·27
NiO	45·15	29·72	21·91	31·28	17·60	...	9	19·04	27·61
CoO	...	...	...	...	...	...	0·15	...	...
MnO	...	...	...	0·20	...	...	0·7	...	...
MgO	2·47	14·97	18·27	3·22	16·03	37·38	22	18·49	6·82
CaO	...	...	...	0·63	0·48	...	0·1	...	...
H_2O	15·55	17·60	15·40	9·21	10·51	20·39	10	12·29	7·74
Chromite	...	...	...	1·20	1·21	...	...	...	...
Totals	99·12	99·89	99·08	99·93	100·43	100·83	100	98·70	96·82

	Frankenstein.		
	7.	8.	9.
SiO_2	47·49	33·28	60–65
Al_2O_3	1·53	14·62	} 6–8
Fe_2O_3	0·48	3·83	
FeO	...	3·56	...
NiO	20·01	5·68	2·9–4·5
MgO	10·18	23·72	8·5–12
CaO	...	1·47	...
H_2O	18·82	13·91	8–15
Totals	98·51	100·07	...

	Asbolane, New Caledonia.			
	10*a*.	10*b*.	10*c*.	10*d*.
SiO_2	3·0	2·20	16·40	23·09
Al_2O_3	...	14·29	14·60	10·30
Fe_2O_3	10·6	8·91	15·50	16·06
Mn_3O_4	46·7	33·62	12·07	17·59
CoO	15·0	7·76	3·00	5·56
NiO	...	1·64	1·48	1·48
MgO	4·8	2·38	...	2·23
CaO	...	...	...	...
H_2O	17·5	29·20	36·95	23·69
Totals	97·6	100·00	100·00	100·00

Nos. 1–4, from New Caledonia; 1*a*–1*c* = Garnierite.—Nos. 2*a*–2*b* = Chocolate ore, rendered impure by admixed chromite.—No. 3 = Meerschaum; (1) is FeO.—No. 4 = Average of the export ore, dried at 100°.—Nos. 5, 6 = Genthite from Riddles and Revda.—Nos. 7–9 from Frankenstein; 7 = Pimelite, 8 = Schuchardite, 9 = Smelting ore.—Nos. 10*a*–*d*, Asbolane from New Caledonia; 10*a* = Clean picked, 10*b*–*d* = Impure.—Manganese is reckoned as Mn_3O_4 and cobalt as CoO, though possibly chiefly MnO_2 and Co_2O_3 are present.

The parent rock of these deposits is in general a more or less serpentinized olivine rock, peridotite, this being principally, as is the case in New Caledonia, Oregon, Webster, etc., a dunite—olivine with some chromite and picotite—though this is frequently accompanied by saxonite or harzburgite—olivine with some enstatite or bronzite—as for instance in New Caledonia and in Oregon. Exceptionally, as at Revda, the parent rock consists of an augite rock serpentinized to antigorite.

The dunite-saxonite, which represents an anchi-monomineral eruptive, in a non-serpentinized state usually contains 40–47 per cent SiO_2, 40–48 per cent MgO, 4–8 per cent $FeO + Fe_2O_3$, 0·5–2·5 per cent Al_2O_3, and 0–2 per cent CaO, that is, remarkably little Al_2O_3 and CaO; furthermore, some Cr_2O_3,[1] frequently 0·1–0·5 per cent MnO, and always some NiO as silicate, this latter being chiefly in the olivine and subordinately in the pyroxene minerals.[2] CoO occurs only in traces. This dunite-saxonite is richer in nickel than is any other rock. The NiO content varies usually between 0·1 and 0·5 per cent, though occasionally it reaches 1 per cent or more. According to analyses by Glasser, the New Caledonian peridotite in particular is remarkably rich in NiO, this rock sometimes containing over 1 per cent.

The hydrated nickel silicates of the German deposits are accompanied principally by hydrated magnesium silicates poor in, or free from nickel, such as gymnite, kerolite, and meerschaum;[3] also by iron-ochre, quartz, hyalite, opal, chalcedony, and chrysoprase containing some nickel; exceptionally also by some magnesite. The chrysoprase of Frankenstein is used as a precious stone; it is also found at Riddles and at Revda. This mineral-association indicates with certainty a deposition from aqueous solution.

The occurrences in New Caledonia, at Frankenstein, Riddles, Webster, and Revda, undoubtedly did not result from the decomposition of arsenide or sulphide nickel ores, such ores having nowhere been found at those places. Looking elsewhere for the genesis of these deposits, from their constant connection with rocks relatively rich in nickel, from their mineral-association, and from their morphology, it may be assumed with certainty, as was demonstrated years ago by Sterry Hunt, Garnier, Foullon, Diller, and others, that these garnierite deposits were formed by leaching of the country-rock.

The view has occasionally been put forward that the origin of the garnierite was connected with a particularly intense serpentinization. Against this, however, it must be remarked that the rock in which garnierite is found, not infrequently, as for instance in New Caledonia and at Riddles in Oregon, consists of a comparatively little serpentinized,

[1] *Ante*, pp. 153, 244. [2] *Ante*, pp. 153, 287. [3] Analysis No. 3.

fairly fresh peridotite containing but 1–5 per cent of H_2O. Further, the serpentine, according to numerous analyses, contains about the same amount of nickel as the rock from which it resulted, and accordingly the small nickel content of the peridotite was, generally speaking, not disturbed in the process of serpentinization. Some investigators[1] considered the occurrences in New Caledonia to have been formed by ascending heated waters, which having extracted nickel, magnesia, silica, etc., from the peridotite and serpentine in depth, deposited them afterwards near the surface in the form of hydrated nickel-magnesium silicates. Such an explanation however is not apt for these occurrences; on the contrary, Glasser in his detailed description gives conclusive evidence that they were formed by weathering processes limited to the surface, while for the deposits at Frankenstein, Beyschlag and Krusch have been able to produce similar evidence.

In New Caledonia, the silica and magnesia of the more or less serpentinized peridotite have near the surface in greater part been removed by the warm tropical rain-water, leaving behind large eluvial deposits, often 5–15 m. thick, of a red earth—*terre rouge*, frequently mistakenly described as *l'argile rouge* or *l'argile ferrugineuse*, though Al_2O_3 is absent—consisting in greater part of iron-ochre. One analysis of this red earth gave, 18·4 per cent of SiO_2, 69·3 per cent Fe_2O_3, 0·5 per cent Al_2O_3, 1·6 per cent NiO, 0·4 per cent $MgO + MnO$, and 9·8 per cent of H_2O.

In process of weathering, the nickel, cobalt, and manganese, together with some magnesia and silica, went into solution, from which solution asbolane on the one hand and garnierite on the other, were subsequently precipitated. The latter in New Caledonia is not accompanied by magnesite or other carbonates; it occurs principally along fractures and crevices in firm rock near the surface, but also as incrustations in the lower part of the eluvial deposits. The asbolane is limited exclusively to the eluvial deposits, though in all probability the solutions which deposited both it and the garnierite were the same. The asbolane, which possesses a certain similarity to manganiferous lake ore, contains 1 part of nickel to some 2–5 parts of cobalt; the garnierite on the other hand contains 1 of cobalt to about 100 of nickel. These two elements have therefore in these deposits become separated, though analytically the separation is not sharp.

Examination of the juxtaposition of the asbolane and garnierite indicates that the cobalt was precipitated earlier than the nickel. The asbolane consists in greater part of highly oxidized manganese oxides, chiefly MnO_2, from which fact, precipitation by oxidation—probably by means of atmospheric oxygen acting upon a neutral solution—may

[1] Heurteau, 1876; de Levat, 1892; and Benoit, 1892.

be assumed. By such means cobalt would be precipitated as oxide with but very little nickel, the greater quantity of which would remain in solution. In this connection we would recall the earlier process of separating cobalt from nickel, which consisted in the addition of chloride of lime to a neutral cobalt-nickel solution, when cobalt oxide with very little nickel oxide was precipitated, while the greater part of the nickel remained in solution.[1]

The peridotite always carries much more nickel than cobalt, namely, about 1 part of cobalt to some 20–50 parts of nickel, and accordingly the asbolane occurs subordinately to the garnierite. At the decomposition of the peridotite or serpentine the small amount of ferrous oxide is in greater part oxidized to ferric oxide—red earth—and but little iron goes into solution; the low iron content of the hydrated nickel silicates is thus explained. The same is approximately the case with the small amount of alumina which occurs in the parent rock. The dunite and saxonite are on the whole exceedingly poor in sulphides, titanic acid, and phosphoric acid, and such compounds are consequently practically absent from the garnierite deposits.

The occurrences at Riddles and Revda appear from the descriptions available also to have been formed by surface weathering. Concerning the deposits at Frankenstein, some investigators assume leaching by heated waters, which, having extracted the nickel from the country-rock in depth, deposited it again near the surface. This explanation does not however agree with the observed phenomena.

The New Caledonian deposits, owing to the large extent of the peridotite, are of great economic importance. In the formation of these deposits the tropical climate may possibly have had something to do with the processes concerned, such a climate greatly promoting surface weathering. In that case a certain analogy to lateritization would exist.

New Caledonia

LITERATURE

J. Garnier. 'La Géologie et les resources minérales de la Nouvelle-Calédonie,' Ann. d. Mines, 6e sér. t. XII., 1867; various treatises in Compt. rend. 82, 1876; Soc. d. Ing. Civils 5, 1887; Revue scientifique, 1895.—E. Heurteau. 'Sur la constitution géologique et les richesses minérales de la Nouvelle-Calédonie,' Ann. d. Mines, 7e sér. t. IX., 1876.—L. Pelatan. 'Les Mines de la Nouvelle-Calédonie' (with geological map of the island), Génie Civil 19, 1891, II.—D. Levat. 'Progrès de la métallurgie du nickel' (together with description of the New Caledonian mines), Ann. d. Mines, 9e sér. t. I., 1892.—F. Benoit. 'Les Mines de nickel de la Nouvelle-Calédonie,' Bull. de la Soc. de l'Ind. Min. St. Etienne, III. 6, 1892.—A. Bernard. L'Archipel de la Nouvelle-Calédonie, Paris, Hachette & Cie, 1895, p. 458, with 2 maps.—Review in Zeit. f. prakt. Geol., 1897, p. 257.—Fr. D. Power.

[1] Vogt, *Geol. Fören. Förh.* XVII., 1892.

'The Mineral Resources of New Caledonia,' Inst. Min. and Met. Abstract of Proceedings, Vol. VIII. p. 44.—Review in Zeit. f. prakt. Geol., 1901, p. 24.—M. Piroutet. 'Sur la géologie d'une partie de la Nouvelle-Calédonie,' Bull. de la Soc. Géol. de France, 4e sér. t. III., 1903.—E. Glasser. 'Rapport au ministre des colonies sur les richesses minérales de la Nouvelle-Calédonie,' Ann. d. Mines, 12e sér. t. IV., 1903, and t. V., 1904.

The island of New Caledonia extends from 20° 5′ to 22° 24′ south latitude; it is 400 km. long, 65 km. wide, and has an area of 16,117 square

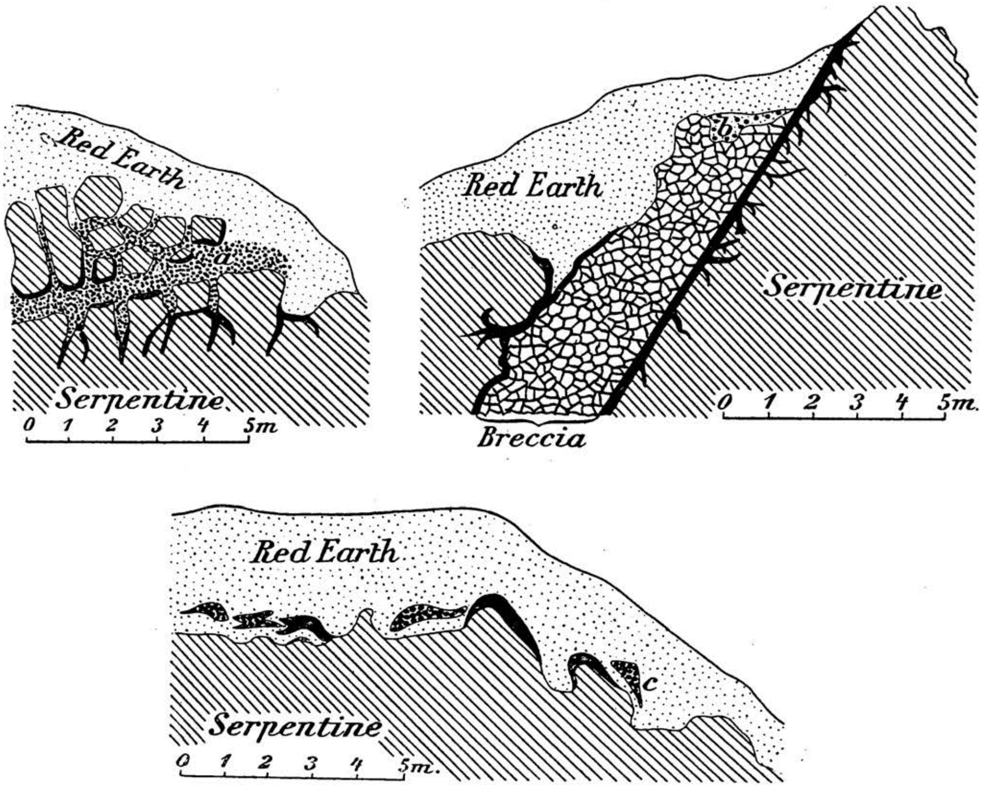


Fig. 397.—Detailed sections of the garnierite deposits of New Caledonia. Glasser.

In the two upper sections the garnierite veins are indicated black; (a) is impure garnierite ore, (b) is red earth with 4-5 per cent of nickel. In the lower section the black crusts on the serpentine indicate asbolane ore; (c) are kidneys of asbolane in red earth.

kilometres. Of this no less than about 6000 sq. km. is occupied by the presumably post- or late Cretaceous, more or less serpentinized peridotite—dunite and saxonite—one field alone covering 3500 sq. km. The serpentine and peridotite areas which, as illustrated in Fig. 156, lie distributed over practically the whole of the island, here perhaps reach the greatest known extent in the world. In these eruptive areas—the more important of which are known under the names of Thio, Canala, Honailou, Mount Kaale, Neporri, etc.—a large number of garnierite deposits occur. At the time of the Paris Exhibition in 1889, no less than about 1200 nickel occurrences had been discovered, and in addition approximately 300 asbolane deposits.

According to Glasser, the hydrated nickel-magnesium silicates are found partly in lodes, partly as the cementing material of a breccia, partly in veins and veinlets in the serpentine, and partly as incrustations within detrital matter consisting principally of red earth. There are no sharp lines between these different modes of occurrence, which on the contrary merge gradually into one another. Principally the very irregular and branched garnierite lodes were first exploited. Upon these lodes some mines reached depths of 108 and even 145 m., though mineralization diminished in depth, and generally speaking the garnierite quickly pinched out. Accordingly, mining was subsequently carried on chiefly in open-cut and only in exceptional cases to a depth of as much as 50 m., the ore usually disappearing at 10–20 metres. In this method of mining great quantities of the eluvial red earth have to be removed. The garnierite lodes only exceptionally reach 1 m. in width; more usually they are narrow stringers which traverse the country-rock in all directions. Of such rock 5–10 cubic metres must frequently be worked in order to obtain 1 ton of ore.

That the garnierite is a result of surface weathering follows, according to Glasser, with certainty from the mode of occurrence. This view is supported by the discovery of insect remains coated with garnierite in the eluvial deposits, as well as by the occurrence of recent garnierite stalactites, which prove that the formation of this mineral still continues.

The asbolane occurs occasionally in small amount in the form of lumps and crusts in the red earth, as illustrated in Fig. 397 *c*.

Mining operations in New Caledonia began in the middle of the 'seventies, the garnierite having been discovered in 1867 and examined in 1873. The extent of operations may be judged from the following figures of ore won, most of which was exported:

From 1875 to 1879 . . .	8,300 tons.
„ 1880 „ 1884 . . .	35,400 „
„ 1885 „ 1889 . . .	42,400 „
„ 1890 „ 1894 . . .	200,300 „
„ 1895 „ 1899 . . .	312,600 „
„ 1900 „ 1904 . . .	539,800 „
„ 1905 „ 1909 . . .	591,800 „
Total to end of 1909 . . .	1,730,600 tons.

From this tonnage of ore, after deducting the loss in smelting, some 105,000 tons of metallic nickel resulted,[1] equivalent to a net content of roughly 6 per cent of nickel. The amount of ore, 960,000 tons, won up

[1] Glasser, *Ann. d. Mines*, 1903, p. 512; and statistics of the *Metall- und Metallurgischen Gesellschaft*, Frankfort-on-the-Maine.

to the year 1902 contained according to Glasser 60,700 tons of nickel, equivalent to 6·3 per cent when deducting nothing for loss in smelting.

The ore won contains much chemically combined water and a considerable amount of mine moisture, which partly disappears when dried at 100°. Dried ore mostly contains at least 7 per cent of nickel, equivalent to 5·4–5·8 per cent in the wet or raw ore. One kilogramme of nickel in dry ore is paid for at the rate of 60–70 centimes in a New Caledonian port; reckoning 60 centimes and assuming the nickel content of the wet ore to be 6 per cent, the price of the ore in such a port would be 36 francs per ton. To this must be added the freight to Europe, which is some 40 francs per ton, so that the value in an English, French, or German port may be taken to be 76 francs, equivalent to 1·27 francs, or roughly one shilling per kg. of nickel.

In raising the value of the ore by hand-sorting to at least 7 per cent in the dry ore, much low-grade ore is lost. For this reason and on account of the high freight to Europe, it is intended to smelt a part of the production at Thio in New Caledonia.

Mining operations, which up to the end of the year 1909 had produced roughly 1,750,000 tons of ore, have exhausted numerous deposits, in spite of which, owing to the exploitation of new deposits, production continues to increase. At the present time some forty mines or opencuts are working.

A few years ago 2000–6000 tons of asbolane containing mostly 3–4 per cent of cobalt were won annually, and up to the year 1904, or approximately in twenty years, some 60,000 tons with an average of 3·5 per cent of cobalt had been exported.[1]

In the New Caledonian serpentine-peridotite many chromite occurrences also occur, some of which are now being exploited.[2]

Frankenstein in Silesia

LITERATURE

J. Roth. Erläuterungen zu der geognostischen Karte vom Niederschlesischen Gebirge und den anliegenden Gegenden. Berlin, 1867.—Th. Liebisch. 'Mineralogisch-petrographische Mitteilungen aus dem Berliner mineralogischen Museum,' Zeit. d. d. geol. Ges., 1877.—H. Traube. Die Minerale Schlesiens. Breslau, 1888.—H. B. v. Foullon. 'Das Vorkommen nickelhaltiger Silikate bei Frankenstein in Preussisch-Schlesien,' Jahrb. d. k. k. Geol. Reichsanst. Vienna, 1892.—B. Kosmann. 'Die Nickelerze von Frankenstein in Schlesien,' Glückauf, 1893, No. 57 and 59.—Aschermann. 'Beiträge zur Kenntnis der Nickelerze von Frankenstein,' Inaug.-Diss. Breslau, 1897.—Illner. 'Das Nickelerzvorkommen bei Frankenstein,' Zeit. f. d. B-, H-, u. S-wesen, 1902.—Albrecht. 'Das Nickelerzvorkommen bei Frankenstein in Schlesien,' Archiv d. k. Geol. Landesanst. Berlin, 1902.—Battig. 'Das Nickelerzvorkommen bei Frankenstein in Schlesien,' Archiv

[1] B. Neumann, in *Die Metalle*, gives 58,730 tons with 3·6 per cent of Co, from 1875–1901.

[2] *Ante*, p. 249.

d. k. Geol. Landesanst. Berlin, 1906.—FLEGEL. 'Das Nickelerzvorkommen bei Frankenstein in Schlesien,' Archiv d. k. Geol. Landesanst. Berlin, 1909.—P. KRUSCH. 'Über die Genesis einiger Mineralien u.s.w. von Frankenstein,' Zeit. d. d. geol. Ges., 1913.

Of the Sudetic foothills which rise through the Diluvial covering between the Eulengebirge and the Zobten-Strehlen mountains, the Baumgarten-Grochau group, south-west of Frankenstein, and the range running through Dittmannsdorf, Prozau, Gläsendorf, Kosemitz, and Disdorf, north of Frankenstein, are unique by reason of their contained nickel deposits.

The group south-west of Frankenstein, owing to the smallness of the deposits, may however hardly be expected ever to become the seat of mining operations. This group, according to Roth, consists of gneiss and of hornblende-schist in part augitic and decomposed to serpentine. In the serpentine and more particularly on the southern slope of Grochberg, magnesite occurring as fissure-filling is exploited. The veins of this material reach 0·5 m. in width and are characterized by great purity. Some nickel ore, the discovery of which led to the grant of several concessions, was found associated with these veins.

The more important nickel deposits at Frankenstein lie north of that town, being confined to four serpentine hills, indicated in Fig. 398, which rise about 377 m. above the Diluvial country and probably belong to one and the same north-south belt. The country-rock of the serpentine consists of gneiss, blue-grey graphitic quartzite-schists with white and red quartz bands, and, particularly in the north and west, of a generally-speaking coarse-grained syenite.

Mining operations for nickel, which were revived in 1891, are being prosecuted upon the four hills, Kosemitz or Mühlberg, Tomnitz, Gläsendorf, and Gumberg. These Silesian nickel mines, in addition to opencuts, have four underground levels at depths of 15–80 m. below the ridge of the Gläsendorf hill.

The serpentine constituting the immediate country-rock of the ore consists of a macroscopic, almost compact mass with a smooth conchoidal fracture, which is usually blackish, olive-green or canary-green in colour, and exhibits stains due to magnetite. It is always very much fractured and more or less decomposed. It contains 41–42·5 per cent of SiO_2, 36–42 per cent MgO, 0·25 per cent Cr_2O_3, and a small amount of nickel which Foullon, from a sample taken from the west slope of Gumberg, gives as 0·34 per cent.

This serpentine, as illustrated in Fig. 399, is traversed by a system of north-northwest quartz veins which split and re-assemble so that their width is very variable, and which provide the resistance to erosion to which the range of hills owes its existence. From these veins as well as from the surface the serpentine became highly altered, to red earth, etc. In this alteration Beyschlag and Krusch differentiate the white decomposition, consisting of a network of magnesite and kerolite, from the grey and green mineralization and the formation of red earth. This last has the greatest extent. It is a red-brown, friable, highly decomposed material, which usually has no sharp separation from the serpentine but often merges gradually into that rock through the less intense decomposition products represented by green and grey ore. The greater part of the red earth occurs immediately at the surface and along the quartz veins. When it occurs silicified it consists, according to microscopic examination by Krusch, in greater part of a mixture of quartz and chalcedony, these minerals exhibiting a banded structure similar to that formed at the gradually widening replacement of a rock by quartz, along a fracture. The cavities between the quartz layers are filled with ferric hydrate.

Green ore consists of masses of red earth or highly decomposed serpentine, traversed by veins of nickel silicate. When the metasomatic replacement of the rock is still more advanced, green knotted ore arises. The term grey ore is applied to a very nickeliferous serpentine which, though under-

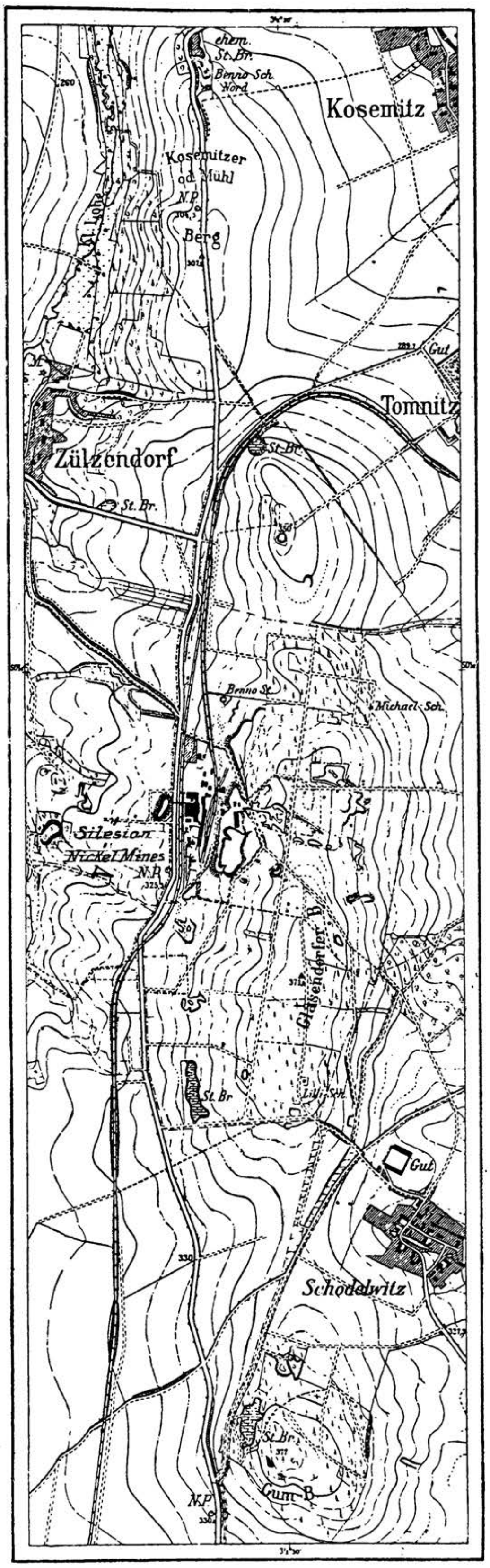


FIG. 398.—The serpentine belt north of Frankenstein in Silesia.

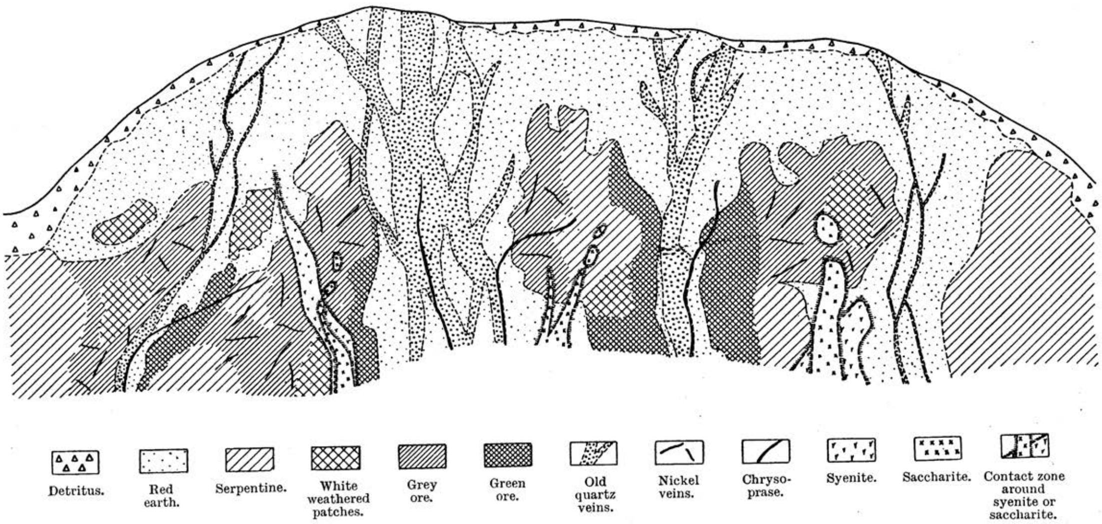


FIG. 399.—Diagrammatic section of the Frankenstein nickel deposits. Scale 1 : 2660. Krusch.

going decomposition, still retains very clearly the character of serpentine, being distinguishable from that rock only by its higher nickel content, which is 1–2 per cent.

The white decomposition of the serpentine is independent of, and older than the formation of the nickel ore ; kernels of white decomposed serpentine are consequently frequently found in the nickel ore and in the red earth, while a more complete replacement of the serpentine has resulted in the formation of white patches. Of the characteristic white minerals, the kerolite is apparently younger than the magnesite, which it replaces.

Chrysoprase is the younger chalcedony coloured a bright green by the small amount of nickel it contains ; in addition, opal and pras-opal also occur. These are in part contemporaneous with, and in part older than the nickel ore.

Saccharite is a white, more seldom grey, mineral aggregate, concerning the origin of which, opinions have hitherto differed. While Glocker believed it to be a special felspar, Liebisch regarded it as a fine-grained assembly of plagioclase crystals in which small green hornblende individuals and blue-black tourmaline were in small amount included. Von Lasaulx and Krusch by microscopic examination found in addition, orthoclase, garnet, diopside, epidote, mica, and a little quartz. One analysis gave 58·9 per cent of SiO_2, 23·5 per cent Al_2O_3, 5·67 per cent CaO, and 7·42 per cent Na_2O. This mineral aggregate occurs vein-like or apophysis-like in the serpentine and its weathered products ; the width of its occurrence in the district of Benno-Süd was proved by boring to be about 50 metres. According to Krusch the saccharite is a differentiation product of the syenite, like which it exhibits contact phenomena.

The green nickel ores represent hydrated nickel-magnesium silicates of very variable qualitative and quantitative composition. All contain principally silica, water, ferrous oxide, ferric oxide, magnesia, and many also alumina. The nickel content varies between very wide limits, the following minerals being distinguished : pimelite, with 2·78–32·66 per cent NiO ; schuchardite, with 5·16–5·78 per cent ; garnierite (?), with 38·61 per cent ; and the above-mentioned green knotted ore. The brown-green variety of this last constitutes the rich ore of the occurrence.

Grey ore, containing 1–2 per cent of nickel and representing a more advanced stage in the decomposition of the serpentine, is a discovery of more recent years.

The nickel ores therefore are associated with red decomposition zones in the serpentine, these in their turn owing their great extent to the quartz veins. As has already been explained,[1] these garnierite occurrences have been formed by immediate lateral secretion, and probably by similar

[1] *Ante*, p. 191.

processes to those which were active in New Caledonia, that is, by decomposition proceeding from the surface and from quartz veins.

The economic importance of Frankenstein, though, it is true, not great, cannot however be ignored. About 10,000–12,000 tons of low-grade ore are produced yearly, such ore being smelted with high-grade ore from New Caledonia.

Riddles in Douglas County, Oregon

LITERATURE

F. W. Clarke and J. S. Diller. 'Some Nickel Ores from Oregon,' Am. Journ. XXXV., 1888.—B. H. v. Foullon. Loc. cit., 1892.—W. L. Austin. Nickel, Second Paper, 'The Nickel Deposits near Riddles, Oregon,' Colorado Scien. Soc. Denver, Jan. 6, 1896.

Within a fairly small area of in part serpentinized saxonite—an olivine-enstatite rock in which the olivine contains 0·26–0·32, and the enstatite or bronzite 0·05 per cent of ferrous nickel—genthite deposits in the form of numerous mostly narrow fissure-fillings carrying some quartz or chrysoprase, occur; these deposits are limited to the neighbourhood of the surface. In addition, nickel hydrosilicate is found in the loose detritus.

In the exploration work prosecuted about the year 1890, impoverishment became apparent at a depth of 15 metres. The country-rock consists partly of serpentine and partly of a slightly-serpentinized saxonite; in this case therefore the nickel silicate cannot be the end product of ordinary serpentinization. In this district also there are at the surface extensive deposits of an impure iron-ochre. The formation of nickel silicate by surface weathering, already discussed when describing New Caledonia, would consequently appear to apply here also.

Austin assumed the action of heated waters. Foullon considered he was able to recognize successive stages in the deposition of the ore. According to him, thin layers, varying in colour from white to sap-green, in which silica, magnesia, very little iron, and some nickel, were contained, were the first to be deposited. Later, in Tertiary time, these in turn became altered, with the result that genthite became deposited in the larger fissures.

Up to 1896 about 3000 tons of ore containing some 5 per cent of nickel had been produced, this production being spread over many years in which operations were only on a small scale. The deposits are of no great importance. At Webster in North Carolina, narrow unpayable stringers of genthite and gymnite, accompanied by some talc, occur in a partly serpentinized dunite.[1]

[1] Clarke and Diller, *loc. cit.*; S. H. Emmons, *Eng. and Min. Journ.*, 1892, p. 476; P. H. Wurtz, *Amer. Ass. Adv. Sc.* XII. p. 24, and *Am. Journ. Sc.* 2, XXVII. p. 24.