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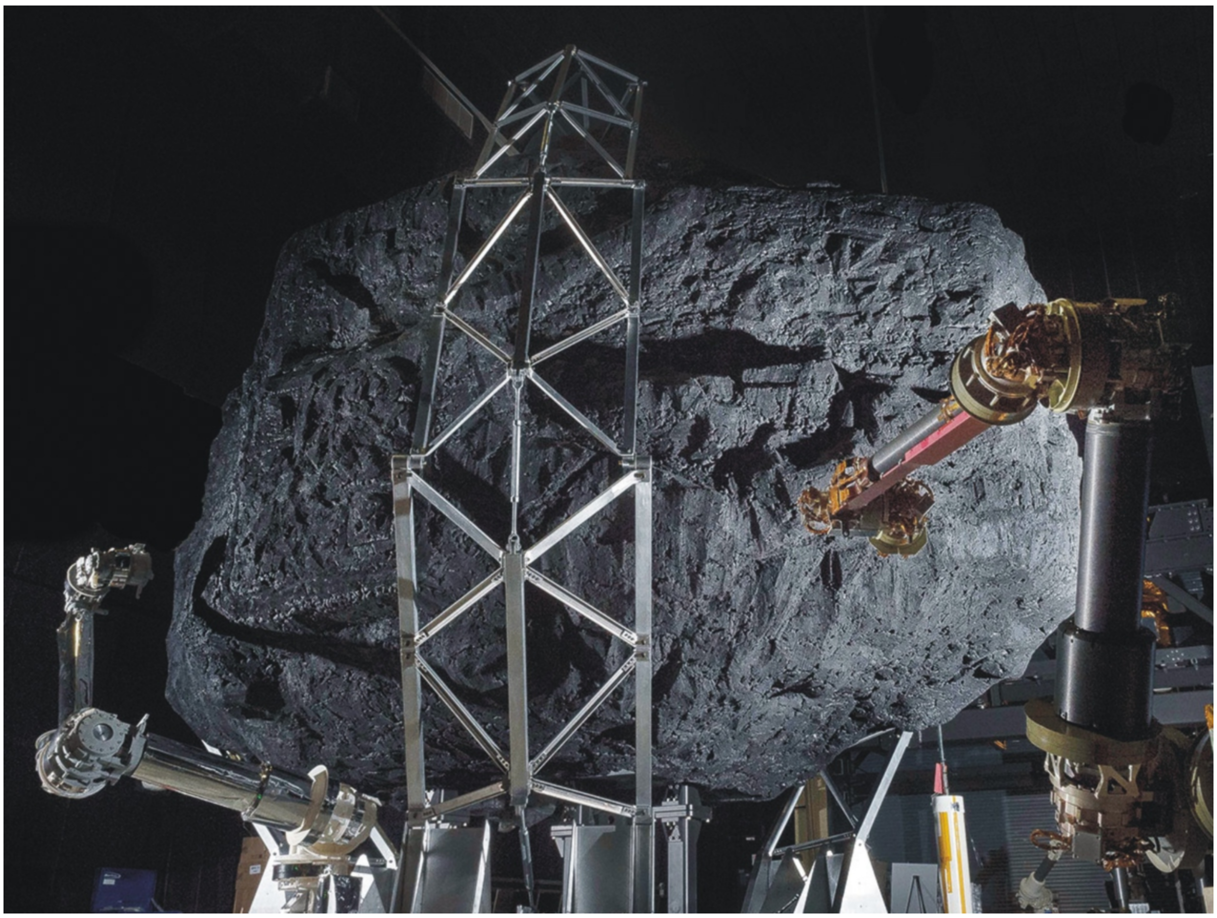

Iron under the Sea - The Tale of Canada's Longest-lived Mine

Prospects for Platinoids from Asteroids

2019 VOLUME 46

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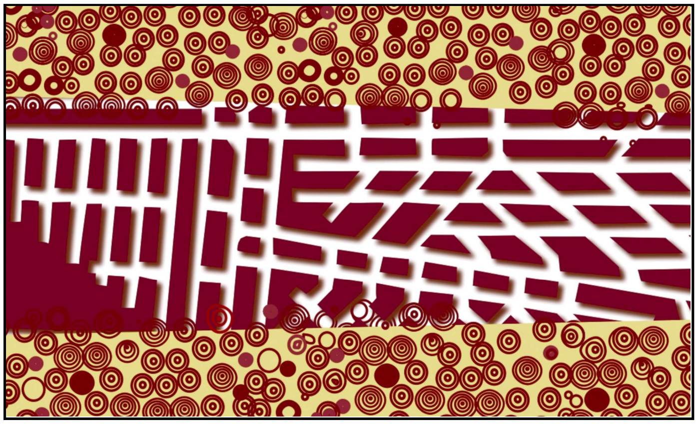
Cover Image: A NASA image from the testing of technology at the Goddard Flight Center, Maryland, intended to recover a boulder from a near-Earth asteroid, and bring it into Earth orbit for further examination. In the image, they are using a 'mock asteroid boulder' for simulation. The boulder is made from wood, styrofoam, aluminum and real rock. Photo Credit: National Aeronautics and Space Administration (NASA).

SERIES



Great Mining Camps of Canada 6. Geology and History of the Wabana Iron Mines, Bell Island, Newfoundland

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Gold is for the mistress—silver for the maid—
Copper for the craftsman cunning at his trade.
"Good!" said the Baron, sitting in his hall,
"But Iron—Cold Iron—is master of them all."

— Rudyard Kipling (1910)

SUMMARY

The Wabana iron mines were in operation from 1895 to 1966, during which time they produced over 80 million tonnes of iron ore. They are hosted by Early Ordovician rocks that contain Clinton-type stratiform ironstones. Mineralization is characterized by oölitic, dark red to purple-red to reddish brown beds of hematite-rich fossiliferous sandstone, siltstone, and shale. Three ironstone beds are of economic importance: the Lower (Dominion Formation), Middle (Scotia Formation) and Upper (Gull Island Formation) with the Lower bed extending over 3.8 km beneath Conception Bay. The iron content in all beds ranges from 45 to 61% with a silica concentration of 6 to 20%.

Reports of iron on Bell Island go back to at least 1578, when a Bristol merchant reported retrieving ore samples for shipment to England. The deposits, however, remained undeveloped for over three centuries until their rediscovery by local fishermen in the late 1880s. In 1895, the Nova Scotia Steel & Coal Company acquired the mining lease for the claims and first ore was produced at surface from No. 1 mine in the Lower bed along the island's northwest coast. By the turn of the twentieth century the Dominion Iron and Steel Company Limited acquired a share of the Bell Island claims, and with surface reserves exhausted, the decision was made by both companies to proceed underground and develop submarine mines. Over the next five decades mining operations were operated by several owners at a steady and at times an expanding rate, with periodic setbacks through two world wars and the Great Depression. The worldwide increase in demand for iron after World War II meant the mines were in full production and exporting over 1.5 million tonnes of ore per annum. In 1950, the unprofitable No. 2 mine was closed, and a series of major expansion projects were launched with the goal to double annual production to 3 million tonnes.

By the 1960s, the Wabana mines faced increased competition from foreign producers, who flooded the world iron market with high-quality ore from low-cost open-pit deposits. The last mine at Wabana ceased operation in 1966 because the high-phosphorus content of the ore was incompatible with the newest steel-making technology and the market for Wabana ore all but disappeared. Over 35 million tonnes of ore was exported to Canada (Nova Scotia) while the remainder was shipped to the United Kingdom and Germany. At the time of closure, the Wabana mines were the oldest, continually producing mine in the country. Annual production peaked in 1960 when over 2.8 million tonnes of concentrated ore were shipped. Enormous potential reserves of several billion tonnes, grading 50% iron, remain in place beneath Conception Bay but the high cost of submarine mining and absence of a market for non-Bessemer ore present obstacles to any future re-development.

RÉSUMÉ

Les mines de fer de Wabana ont été en activité de 1895 à 1966, période durant laquelle elles ont produit plus de 80 millions de tonnes de minerai de fer. Elles renferment des roches de l'Ordovicien inférieur contenant des roches ferrugineuses stratiformes de type Clinton. La minéralisation est caractérisée par des couches de grès oolitiques, de silts et d'argiles couleur

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rouge foncé à rouge violacé à brun rougeâtre, fossilifères et riches en hématite. Trois gisements de roches ferrugineuses ont une importance économique: la couche inférieure (Formation Dominion), la couche intermédiaire (Formation Scotia), et la couche supérieure (Formation Gull Island), la couche inférieure s'étendant sur 3,8 km sous la baie de la Conception. La teneur en fer de toutes les couches varie de 45 à 61% avec une concentration en silice de 6 à 20%.

La présence de fer sur l'île Bell a été signalée depuis au moins 1578, lorsqu'un commerçant de Bristol a rapporté avoir récupéré des échantillons de minerai pour les expédier en Angleterre. Toutefois, les gisements sont restés inexploités pendant plus de trois siècles jusqu'à leur redécouverte par des pêcheurs locaux à la fin des années 1880. En 1895, la Nova Scotia Steel & Coal Company acquit le bail minier pour les droits et le premier minerai fut produit à la surface de la mine numéro 1 située dans la couche Inférieure sur la côte nord-ouest de l'île. Au tournant du XXe siècle, la Dominion Iron et la Steel Company Limited acquit une part des droits de l'île Bell. Les réserves de surface étant épuisées, les deux sociétés prirent la décision de procéder à des travaux souterrains et de développer des mines sous-marines. Au cours des cinq décennies qui ont suivies, plusieurs propriétaires ont exploité les mines à un rythme soutenu et parfois en expansion, avec des reculs périodiques à la suite des deux guerres mondiales et de la Grande Dépression. L'augmentation de la demande de fer dans le monde après la Seconde Guerre mondiale s'est traduite par une pleine production des mines et une exportation de plus de 1,5 million de tonnes de minerai par an. En 1950, la mine numéro 2, non rentable, a été fermée et une série d'importants projets d'expansion ont été lancés dans le but de doubler la production annuelle à 3 millions de tonnes.

Dans les années 1960, les mines de Wabana ont dû faire face à une concurrence accrue des producteurs étrangers, qui ont inondé le marché mondial du fer avec du minerai de haute qualité provenant de gisements à ciel ouvert à faible coût. La dernière mine de Wabana a cessé ses activités en 1966 parce que la teneur élevée en phosphore du minerai était incompatible avec la technologie de fabrication de l'acier la plus récente et que le marché du minerai de Wabana avait pratiquement disparu. Plus de 35 millions de tonnes de minerai ont été exportées au Canada (Nouvelle-Écosse) alors que le reste était expédié au Royaume-Uni et en Allemagne. Au moment de leur fermeture, les mines de Wabana étaient les plus anciennes mines en production du pays. La production annuelle a atteint un sommet en 1960 lorsque plus de 2,8 millions de tonnes de minerai concentré ont été expédiées. D'énormes réserves potentielles de plusieurs milliards de tonnes, contenant 50% de fer, restent en place sous la baie de Conception, mais le coût élevé de l'exploitation minière sous-marine et l'absence de marché pour le minerai non Bessemer constituent des obstacles à tout futur redéveloppement.

Traduit par la Traductrice

PREAMBLE

Iron is the most abundant metallic element on Earth, comprising ca. five per cent of the Earth's crust, but it is the dominant component of Earth's core. Iron's abundance on Earth is due to its profuse production in the core of high-mass stars, where it is the final element to be generated by a series of nuclear fusion reactions between atoms. Iron is a transition metal that exists in a wide range of oxidation states and it is widely distributed throughout rocks in silicate minerals (e.g. chamosite – $(Fe_{2+},Mg)_5Al(AlSi_3O_{10})(OH)_8$) and concentrated in oxide (e.g. hematite – Fe_2O_3 and magnetite – Fe_3O_4), sulphide (e.g. pyrite – FeS_2) and carbonate (e.g. siderite – $FeCO_3$) minerals in ironstones and iron formation.

Mankind's initial production of iron from its ores began around 2000 BC during the Bronze Age in Mesopotamia. The working and use of iron (and its alloy steel), however, did not become widespread until the Hittites of Anatolia developed the methods to remove deleterious impurities by smelting, at which point iron displaced bronze as the dominant tool and weapon material denoting the start of the Iron Age ca. 1200 BC.

Subsequently, the art of forging steel from iron spread rapidly through the ancient world from Asia Minor into China, India, North Africa, and Europe. The Carthaginians, Romans, and Vikings conquered territories and created empires by their exploitation of iron. Changing wrought iron into steel, however, proved difficult; thus high quality steel was not produced until the technological advances of clockmaker Benjamin Huntsman (1704–1776) in Sheffield, England.

Huntsman was trying to develop improved quality watch springs and invented the crucible process for casting steel ca. 1740, whereby wrought iron and steel were used as raw materials to liberate slag from blister steel while simultaneously increasing the carbon content by cementation with powdered charcoal. Huntsman's process used a coke-fired furnace to achieve temperatures of up to 1600°C to fully melt steel in alumina clay crucibles. Added siliceous fluxes removed inhomogeneities in the steel, and caused carbon to dissolve evenly into the liquid crucible—or cast—steel, thereby improving its yield strength and hardness.

Steel is an iron-carbon alloy containing additional elements that can be produced into thousands of varied compositions to meet a wide range of society's requirements. Since the 19^{th} century the industrial development of nations has been overwhelmingly measured by the size and quality of their iron resources, and by their ability to transform that iron into vast amounts of steel. Technological advances in the iron industry played a key role in creating modern economies that are dependent on a variety of steel products. Iron is therefore the foremost index of industrialization and the *sine qua non* of modern civilization.

The Wabana iron mines are located on Bell Island in Conception Bay, eastern Newfoundland (Fig. 1). The iron deposits are hosted by a sequence of Early Ordovician (Floian; ca. 470–477 Ma), relatively flat lying, fine-grained clastic and chemical sedimentary rocks. Ironstone occurs in six zones and was mined from three stratigraphic units. These deposits were in operation continuously from 1895 to 1966 and produced over 80 million tonnes of iron ore.

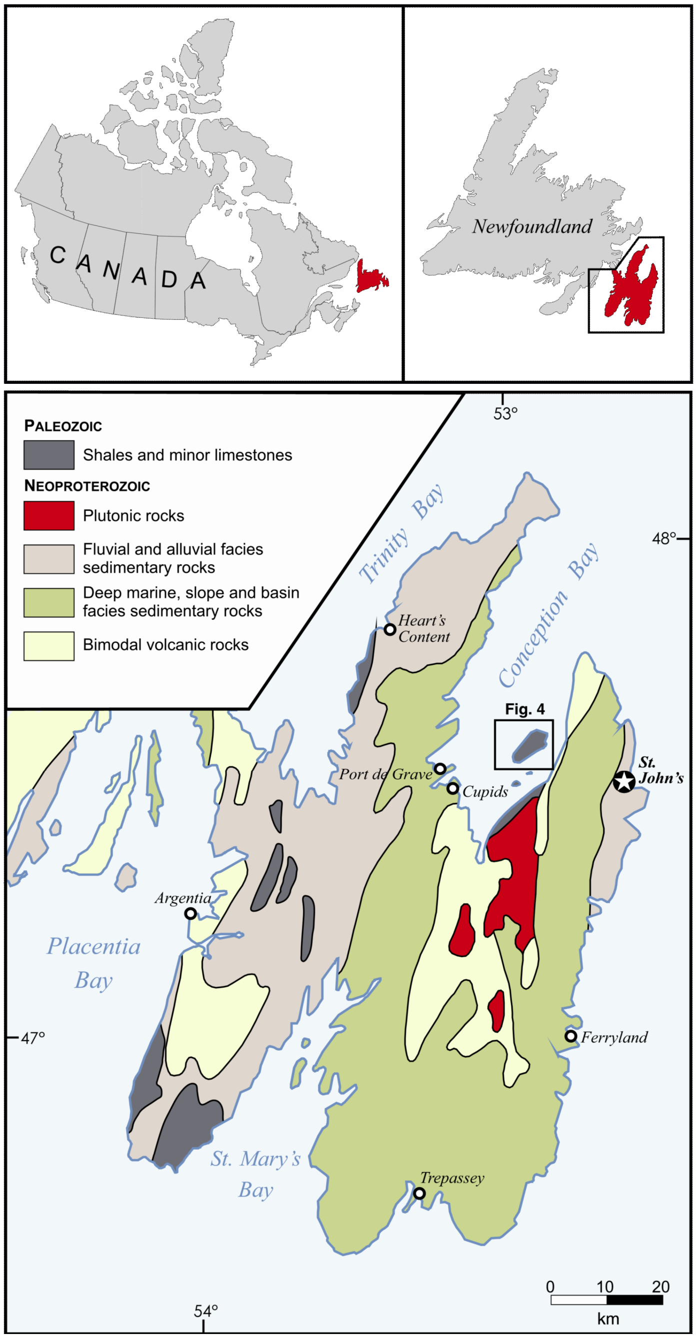

Figure 1. Location maps and geology of the Avalon Peninsula, eastern Newfoundland. Source from the Geological Survey of Newfoundland and Labrador.

This paper is a synthesis of available published information on the geological and historical characteristics of exploration and mining on Bell Island. It relies on the thorough and extensive research by numerous authors including: Martin (1983) and Weir (1986), who chronicle the historical aspects; Anson (1951) and Southey (1969), who outline submarine mining methods; and Hayes (1915) and Ranger (1979) who describe the mineralization and geology.

HISTORY OF EXPLORATION

Mineral deposits have long been sought after since Europeans first explored the New World. Iron was the first metal to be mined by Europeans in North America ca. 1000 AD. The smelted slag remnants of iron oxyhydroxide (i.e. bog iron) deposits worked by the Vikings are preserved in the Norse colony of Vinland at L'Anse aux Meadows, Newfoundland. The earliest documented references to iron, however, are from Bristol merchant Anthony Parkhurst (fl. 1561–1583) who visited Newfoundland in 1575. In a 1578 letter to Richard Hakluyt (1553–1616), Parkhurst extols the natural resources of Newfoundland with specific reference to the prospects of iron mining and smelting, and of finding *"certain Mines…in the Island of Iron, which things might turn to our great benefit."* Parkhurst mentions that he recovered iron samples from the *Island of Iron* [Bell Island] for return to England. This letter to Hakluyt was the first to support English settlement of the New World and was no doubt a factor in the royal charter granted to Sir Humphrey Gilbert (1539–1583) by Queen Elizabeth I (1533–1603) to establish the first colony in North America (Hall 1882). When Sir Humphrey landed in St. John's on 5 August 1583 and formally took possession of the harbour, he brought with him a Saxon mineral expert, Daniel of Buda, who collected iron ore from the colonial area governed by Gilbert. Unfortunately, Daniel and his ore never made it to England as his ship, *Delight*, ran aground and broke up on 29 August 1583 during her return voyage (Martin 1983).

Interest in Bell Island iron waned for the next several decades until King James VI (of Scotland) and I of England (1566–1625) granted a group of merchants of the London and Bristol Company letters patent to fortify the settlement of Cuper's Cove (now Cupids). In 1610, a group of colonists under Governor John Guy (1568–1629) landed on Newfoundland with specific instructions for regulation of the fishery and to report on the likelihood of exploitable mineral resources. Early reports from the colonists (known as planters) indicated iron deposits on Bell Island, of which Guy viewed as an augury of prosperity. He proposed that iron could be smelted and produced more cheaply in Newfoundland and shipped to England as ballast on schooners to reduce freight costs. Henry Crout (fl. 1612–1617), council member in the London and Bristol Company, visited Bell Island and reported that *"the like land is not in Newfoundland for good earth and great hope of Irone stone"* (Cell 1969). Lord Proprietor Sir Percival Willoughby (1560–1643) was so impressed by Crout's report that he sent his son and six apprentices to Newfoundland in 1612 to develop Willoughby's own tract of land in Conception Bay, of which he insisted that Bell Island be included. Sir Percival was unsuccessful in convincing other shareholders in the London and Bristol Company to grant his request as the enterprise decided to reserve for itself a portion of the mineral wealth of Bell Island (Cell 1969). The first reference to production of iron on Bell Island is by Reverend Lewis Amadeus Anspach (1770–1823), who in 1819 mentions *"an iron-mine at Back Cove, on the northern side of Bell Isle."*

The earliest geological reference to Bell Island was by Cambridge geologist Joseph B. Jukes (1811–1869) who reconnoitered Conception Bay in 1839 as part of the first geological survey of the country. Jukes (1842) reported a bed of *"bright*

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red sandstone about eight feet thick" as cropping out on the northwest side of the island but makes no reference to any mine working the deposit.

Irish farmers who settled Bell Island in the 19th century are noted for one distinctive feature—they farmed for profit, in contrast to others who farmed mainly for subsistence. This market-oriented commercialism meant that the Irish had to regularly transport their produce to markets in St. John's by schooner; their anchors, known locally as killicks, were constructed using the heavy 'red rock' as ballast, by enclosing it in frames of young fir trees. Word of the extraordinarily heavy rocks of Bell Island, and its suitability for ballast, spread throughout the residents of Conception Bay and was the reason for the development of the mines.

In the late 1880s, Jabez Butler (1835–1924) was sailing to St. John's from Port de Grave when he was forced to land on the north side of Bell Island to wait out a storm. He took on ballast from the loose rock on the shore and continued to St. John's. While unloading the rock upon the wharf at St. John's, Butler was approached by an English captain who noticed the rock's apparent iron content and offered to take it to England to be assayed. After his return to the United Kingdom, the captain wanting additional rock wrote to Butler requesting "50 pounds for analysis"; Butler misinterpreted the request by thinking the captain wanted the fee of £50 and did not reply (Fay 1956).

Butler would have probably ignored Bell Island, if not for one of his sons who later emigrated to Canada and asked his father to send the rock to Montreal for analysis. The results came back positive and he sent a telegraph to his father who on 4 August 1892 filed for a mineral lease for three claims on the north side of Bell Island (Fig. 2). The Butler family (Fig. 3), lacking the financial resources to develop the claims engaged the St. John's merchant company Shirran & Pippy in May 1893 as an agent to promote the property. The latter agreed to lease the three claims for 20% of the profits and by the summer of 1893 brought in A. Robert Chambers (1879–1937), chief engineer of the New Glasgow Coal, Iron and Railroad Company of Trenton, Nova Scotia to survey the claims. Chambers immediately recognized the value of the property and negotiated with Messrs. Shirran and Pippy to acquire the land title. On 3 September 1894, the New Glasgow Coal, Iron and Railroad Company acquired the mining lease for the three claims for $1000 and a royalty of 5 cents per tonne on all processed and shipped ore; Chambers also negotiated a future purchase option for all claims of the Butler family (Martin 1983).

REGIONAL GEOLOGICAL SETTING

The Avalon Peninsula (part of Avalonia), represents a far-traveled accreted terrane that forms the eastern flank of the Appalachian–Caledonian orogen (Pollock et al. 2012). It comprises four, lithologically different Neoproterozoic rock units, which are unconformably overlain by Early Paleozoic strata that constitute Bell Island (Fig. 1). The oldest Neoproterozoic (pre-570 Ma) rocks comprise a bimodal, predominantly volcanic assemblage that is intruded by co-magmatic plutonic rocks (O'Brien et al. 2001), which record a protracted and

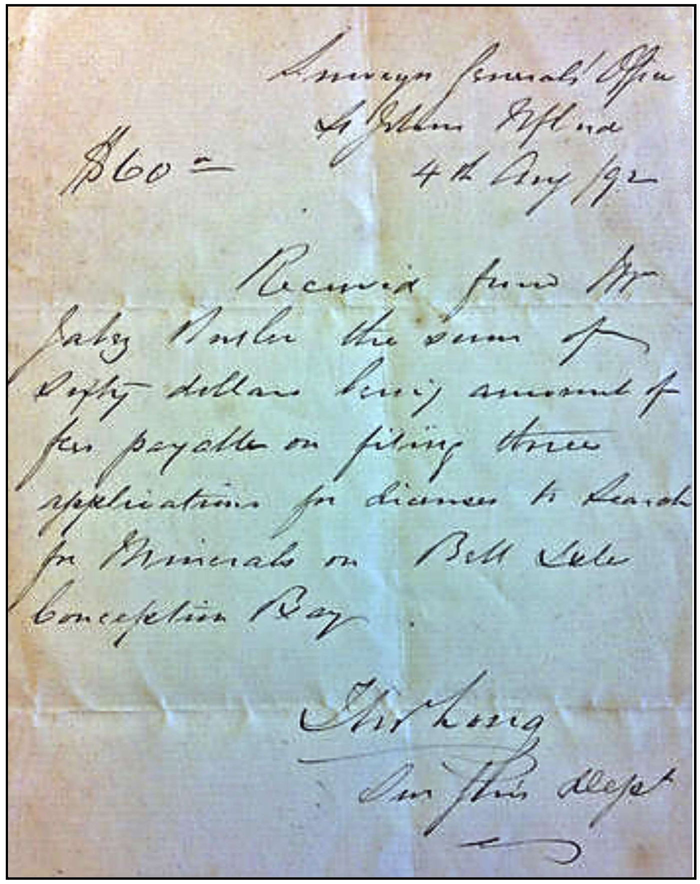
Surveyor General's Office
St. John's Nfld
$60 — 4th Aug /92
Received from Mr
Jabez Butler the sum of
sixty dollars being amount of
fees payable on filing three
applications for licenses to search
for Minerals on Bell Isle
Conception Bay.
Long
for this dept

Figure 2. Receipt in the amount of $60 filed by Mr. Jabez Butler on 4 August 1892 for *"…fees payable on filing three applications for licenses to search for Minerals on Bell Isle Conception Bay."* Courtesy of The Rooms Provincial Archives, Newfoundland and Labrador.

episodic subduction-related tectono-magmatic history (O'Brien et al. 1996). They are unconformably overlain by pre-570 Ma, deep-marine, siliciclastic rocks that are in turn conformably overlain by post-570 Ma shallow marine to terrestrial rocks of alluvial and fluvial origin (O'Brien et al. 2001).

The fine-grained, siliciclastic-dominated succession that unconformably overlies different parts of the Neoproterozoic rocks in Avalonia heralds the transition to widespread platformal sedimentation in the latest Neoproterozoic. Deposition of sedimentary rocks in the Ediacaran continued into the Early Ordovician on Bell Island, where two groups of rocks have been delineated (Fig. 4). The older Bell Island Group comprises a 1500 m-thick sequence of interbedded micaceous sandstone, siltstone, shale, and ironstone, which are interpreted as shoreline sediments. It is overlain by somewhat deeper-water deltaic and shallow marine deposits of the 257 m-thick Wabana Group on the north part of the island (Ranger 1979; Williams 1990). Ironstone occurs in the Beach and Dominion formations of the Bell Island Group and in the Scotia and Gull Island formations of the Wabana Group (Ranger et al. 1984). Ironstone occurs in six zones (Fig. 5) and was mined from the Lower, Middle and Upper ore beds; these are described in detail, with plans (Fig. 6) and cross sections (Fig. 7) by Lyons (1957).

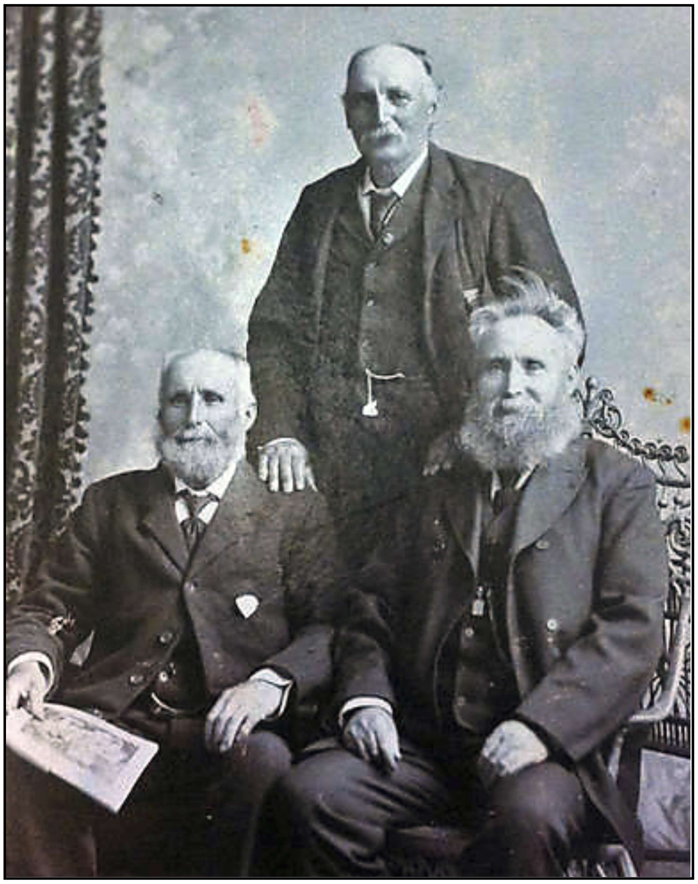

Figure 3. Brothers James, John, and Esau Butler; sons of Jabez Butler—the discoverer of the Wabana deposits. Courtesy of The Rooms Provincial Archives (Newfoundland and Labrador).

Zones 0 and 1, are thin oölitic hematite bands, each 1 m thick, that are exposed along the southwest and along the east coast of Bell Island, respectively. The two zones were termed the McGraw and Eastern Head ore beds by van Ingen (1914), and both were subsequently elevated to member status of the Beach Formation by Ranger et al. (1984).

The Lower (Dominion) bed (zone 2) consists of granular ironstone with several oölitic hematite-rich lenses interbedded with lenses of shale and sandstone. The surface exposure, which has been mostly removed by strip mining, is approximately 4 m in thickness, but underground the formation increases to 15 m in the No. 3 mine. The Dominion is the thickest ore zone and provided most of the ore that was mined. The upper 10 m of the bed contains a good quality ore of concentrically coated hematite-chamosite grains having 45 to 57% iron and 7.5 to 20% silica. The lateral continuity of the Dominion bed has been delineated in the submarine workings and extends down dip from the surface of Bell Island for 5200 m and along strike for 6100 m without termination (Southey 1969).

Zone 3 comprises three beds of pyritic oölitic ironstone and phosphatic and pyrite-coated shale pebbles that range in thickness from 5 cm to 1.5 m (Hayes 1915). This zone formed an important marker horizon during mining (A.F. King in Ranger et al. 1984) and was referred to as the "pyrite bed" (van

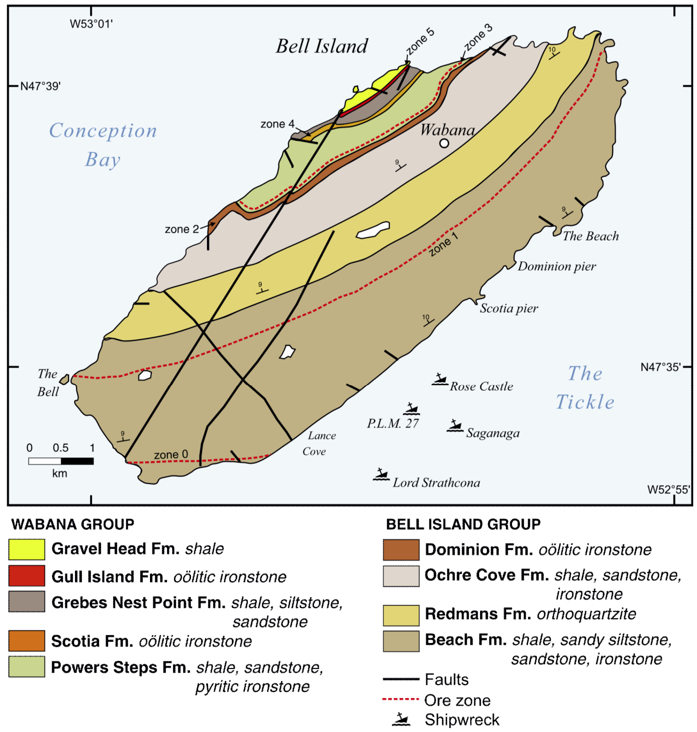

Figure 4. Geology of Bell Island, Conception Bay, Newfoundland (modified from Todd et al. 2019).

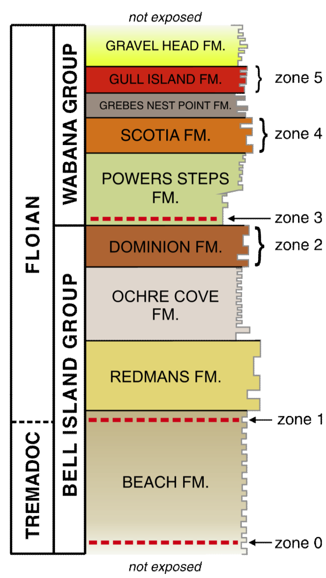

Figure 5. Simplified stratigraphy of the Bell Island and Wabana groups and ore zones (modified from Ranger et al. 1984).

Ingen 1914). The oölitic ironstone beds are interbedded with black shale containing stringers of pyritic shale pebble conglomerates in the basal 6 m of the Powers Steps Formation that stratigraphically lies immediately above the Lower bed.

The Middle, or Scotia, bed (zone 4) lies 60 m above the Dominion bed and comprises oölitic, reddish brown ironstone. The oölites consist of hematite and chamosite. The bed varies in thickness from 2 to 3 m with an average mined thick-

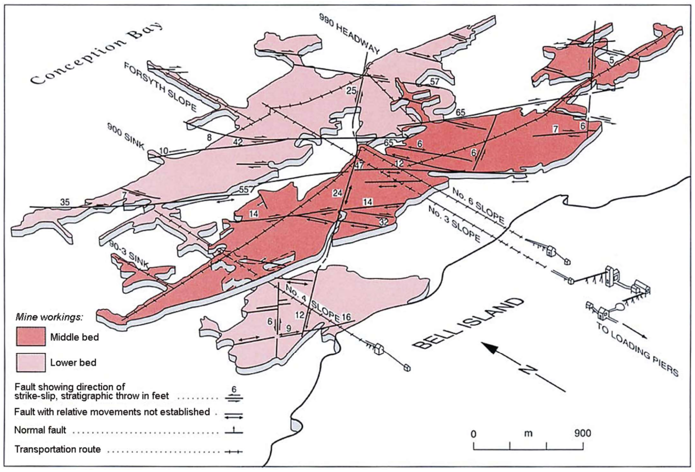

Figure 6. Schematic map of submarine mine workings showing ore trend and extent beneath Conception Bay (Lyons 1957).

ness of 2.5 m (Ranger 1979). A 10–15 cm thick distinctive grey bed of chamosite oölites forms the upper part of the formation with minor siderite, quartz, and phosphate nodules. The composition of the ore ranged from 51.5 to 59.6% iron and 6.4 to 12% silica. The bed extends to the northwest for 1370 m beneath Conception Bay and along strike for at least 2440 m (Southey 1969).

The Gull Island Formation includes the Upper bed (zone 5), which lies 10 to 15 m stratigraphically above the Scotia bed and is distinguished by interfingering lenses of hematite with concentric layers of chamosite and hematite with interstices containing siderite. Thin layers and lenses of hematitic shale and fine-grained sandstone are interbedded with the ore. Individual beds are up to 55 cm in thickness but are typically thinner. This formation has a maximum thickness of 3 m and marks the upper limit of iron deposition in the sequence (Ranger et al. 1984). The Gull Island Formation was only mined on the surface and never exploited in the submarine workings because of its relatively low iron content (48.6–51.8%), lateral irregularity in thickness, and proximity to the ocean floor.

Collectively, the Lower, Middle, and Upper beds are referred to as the Wabana deposits and they were affected by two ages of faults distinguished by their displacement and orientation relative to the general trend of the three ore zones (Norris 1956; Lyons 1957). The older faults trend northwest (290°), dip steeply (85°) to the southwest, and generally have oblique, dextral offsets of a few tens of metres. These structures are transected by several well-defined faults that strike northeast (030°) and dip 80° to the southeast with sinistral motion. An apparent vertical displacement of up to 30 m is recorded on both sets of faults. A conjugate joint set developed subparallel to the faults is prominent throughout the area. The joints are widely spaced (30 cm) in competent ore beds and are more closely spaced (10 cm) in siltstone.

NATURE OF MINERALIZATION AND GENESIS

Mineral deposits are naturally occurring anomalous concentrations of metals or minerals in the Earth's crust formed by geological processes. An iron ore deposit must contain enough iron-bearing minerals (at least 25% iron) to be mined and refined (often via smelting) for profit. The best ores have the highest iron content and the lowest concentration of slag-forming constituents such as silica, alumina, phosphorous, sulphur, manganese, and additional ferride-group elements. They must also meet the grade, quality, and composition specifications for a particular smelting and steel making technology, either as direct-shipped ore or after beneficiation to improve their physical and chemical properties.

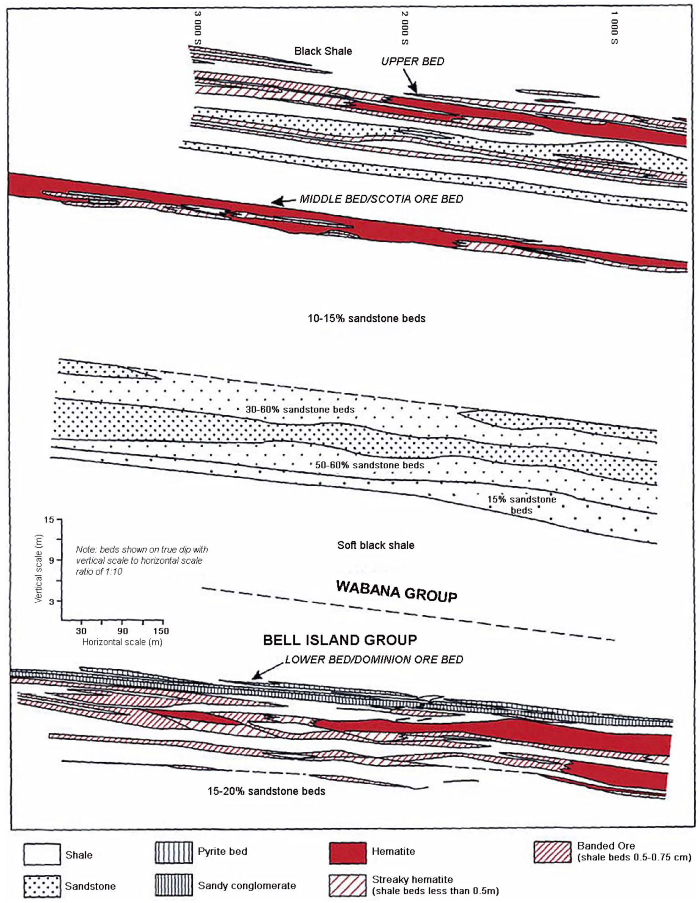

Figure 7. Cross section through the Upper, Middle, and Lower beds of the Dominion, Scotia, and Gull Island formations (Lyons 1957).

The name Clinton-type ironstones was attributed by Lindgren (1933) to Smyth (1892). Smyth (1892) described the "Clinton iron ore" as detrital sedimentary rocks containing oöids, pisoids of siderite and chamosite, with clasts of silica-rich, aluminous goethite. Clinton-type deposits are characterized by high alumina and phosphorous contents. They have formed since the Neoproterozoic and occur in various sedimentary environments. However, the majority of Phanerozoic oölitic ironstones have primary sedimentary features such as crossbedding, ripple marks and raindrop impressions, indicative of a shallow marine environment (Kimberley 1979).

Wabana ores, which Lindgren (1933) briefly described, are characterized by oölitic, dark red to purple-red to reddish brown beds of massive ironstone. The oölites are formed around nuclei of fossil fragments or granules and comprise alternating concentric rings of hematite, or chamosite and hematite (Ranger 1979). Interstices contain siderite, quartz, phosphatic shell debris and nodules, and minor pyrite. Fine-grained detrital sand constitutes up to 10% of the ironstone as nucleii to oölites or in interstices between oölites (Hayes 1915). The outer layers of the oölites are predominantly composed of hematite with the spherules averaging less than 1 mm in thickness. Local concentrations of siderite are typically present in the matrix. Zones rich in siderite commonly contain a high concentration of manganese. Oölitic pyrite occurs throughout the sequence and is composed of concentric layers of pyrite with alternating layers of calcium phosphate (Ranger et al. 1984). Thin beds and lenses of hematitic shale and fine-grained sandstone are associated with the oölite ironstone. The best Wabana ore had minimal shale and a high proportion of hematite and chamosite relative to siderite.

A genetic model for the formation of ironstone must account for the quantity of iron, environment of deposition, tectonic setting, and the biological, physical and chemical factors obtained at the time of deposition. Temporal and spatial controls on mineralization, and the erratic distribution of ironstone beds, indicate that the oölitic ironstone, ferruginous shale, and sandstone beds were deposited by primary sedimentary processes. Sedimentary structures indicative of a shallow marine environment, in addition to sequence stratigraphy and facies relationships (Todd et al. 2019), suggest deposition during an overall marine transgression punctuated by higher order sea level fluctuations. The depositional environment is interpreted as a transition zone from terrigenous clastic sedimentation to chemical sedimentation, i.e. in tidal or barrier bars within an overall lagoonal environment. The ironstone oölites represent primary oxyhydroxide precipitates that were transported onto the bar by small-scale sea level fluctuations related to tidal or storm currents. Precipitation of chamosite and goethite-bearing oölites occurred during periods of sediment starvation in subtidal and intertidal environments with later diagenetic transformation to hematite during dehydration (Ranger 1979).

The source(s) and primary processes for the deposition of iron in Clinton-type deposits have long been considered enigmatic (Gross 1967). The source of the enormous quantity of iron in the Wabana deposits was interpreted by Hayes (1915) to result from terrestrial weathering of crystalline rocks, causing iron to be transported in solution and deposited in a restricted basin by chemical precipitation while clastic sediments were being deposited. Ferric iron, however, is highly insoluble in oxygenated surface water, and the abundance of shale and coarse-grained sandstone interbedded with the iron beds are not compatible with this hypothesis (Gross 1995). Most recently, Todd et al. (2019) have proposed that the iron in the Wabana deposits was derived by coastal upwelling of deep, anoxic, nutrient-rich and iron-rich seawater in the vicinity of the site of deposition.

DEVELOPMENT AND PRODUCTION

Development of the mines began under the supervision of Robert Chambers in spring of 1895 with the construction of a loading pier on the southeast side of Bell Island along with a tramway to transport ore from the mine. While construction operations were underway, the New Glasgow Coal, Iron and Railroad Company merged with the Nova Scotia Forge Company to form the Nova Scotia Steel and Coal Company (Scotia Company). The secretary of this new enterprise, Thomas Cantley (1857–1945), in 1911 gave the mine site the name Wabana—an Abenaki word which means "first dawn."

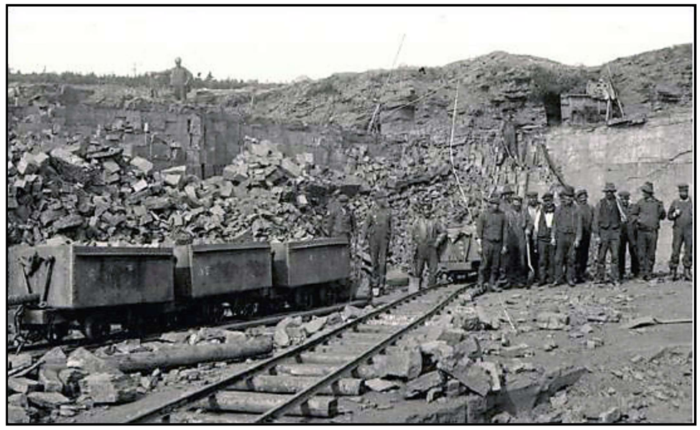

Figure 8. Surface mining at No. 1 mine, Scotia Company ca. 1902. Source: Memorial University of Newfoundland–Digital Archives Initiative.

First ore was produced at surface from the No. 1 mine along the island's northwest coast (Fig. 8). This entailed the removal of thick fir forest and stripping of 9 m of overburden to expose the Lower bed (zone 2) of the Dominion Formation. The No. 5 surface mine in the Scotia Formation was developed soon after. Hematite ore was originally extracted by open-cast mining and hand-picked (or cobbed) to upgrade it; the ore broke into rhombohedral fragments, ca. 20 cm in length, along a conjugate joint-set when stuck by a pickaxe. These fragments were cobbed by boys and loaded into 1.6 tonne cable-driven ore cars for transport by a 3.2 km, endless rope and double track tramway to storage bins at the loading pier.

The first shipload of direct-shipped ore left Bell Island on Christmas Day 1895, destined for the blast furnace in the company town of Ferrona in Pictou County, Nova Scotia. The strategic location of Bell Island along the great circle shipping route between North America and Europe provided ready access to larger markets. The first ore shipped to the USA was on 3 July 1896 and the following year the first trans-Atlantic shipment left Bell Island on 22 November for Europe via the Port of Rotterdam.

Soon after production commenced at Wabana, geologists working for the Scotia Company recognized that the ore beds extended northwest across the island and beneath Conception Bay. At this time, American industrialist Henry Melville Whitney (1839–1923), through the Dominion Coal Company Limited, began to consolidate numerous lease-holdings of the coalfields on Cape Breton, while searching for a source of iron ore for a planned steel mill. In 1899, Whitney incorporated the Dominion Iron and Steel Company Limited (Dominion Company) and began discussions with the Scotia Company to acquire a share of the Bell Island claims. After acquiring fee

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simple title, by exercising their $120,000 purchase option with the Butlers on 4 March 1899—originally negotiated by Chambers five year previous—the Scotia Company entered into agreement to sell a portion of their Bell Island holdings to the Dominion Co. The latter purchased the land claims for the Lower and Upper beds for $1.1 million, and a submarine claim of 22 km^2 for all beds that lay adjacent to the shoreline. The Scotia Company reserved for themselves the on-land component of the high-quality Middle bed and the submarine parts of all three beds that were over 1.8 km from the shoreline, which totaled 215 km^2.

In 1900, with the proceeds from the sale, the Scotia Company purchased the General Mining Association coal holdings in Nova Scotia and began relocation of its steel production from Ferrona to a new steel plant with a single 275-tonne blast furnace and three 45-tonne open hearth furnaces in Sydney Mines. At the same time, Whitney's Dominion Company began construction of a much larger steel mill in Sydney comprising four blast furnaces and ten open hearth furnaces. First steel was produced from the Dominion steel works on 31 December 1901, with production from the Scotia plant soon after in 1902. Both plants utilized Wabana iron ore exclusively in their steel industry.

By 1902 the surface mines were becoming depleted and the decision was made by both the Dominion and Scotia companies to proceed underground and develop the submarine deposits. The No. 5 mine in the Middle bed was exhausted by 1905, and the Scotia Company reached an agreement with the Dominion Company to allow the Scotia slopes (adits) to pass through the submarine areas held by Dominion. In March 1905, the first submarine slope was constructed by the Scotia Company in the Middle bed. Driving the slope proceeded at an average rate of 1.2 m per day at an eight degree dip to the northwest and by 1909 reached the Scotia Company claims at 1.8 km offshore at a depth of 125 m (Chambers and Chambers 1909). Submarine diamond drilling indicated that the Lower bed in the Scotia claim increased in both thickness (15 m) and ore grade, and in March 1910 the Scotia Company decided to increase the gradient of the slope to 30 degrees and mine both beds.

The Dominion Company extracted ore from two submarine inclines, No. 2 and No. 4, which were begun in 1904 and 1916, respectively (Fig. 9). A new double (twinned) slope (No. 3) was constructed by the Scotia Company from the foot of No. 6 slope in 1918 to access the deepest area of the Lower bed (Fig. 10). A single-track haulage level was driven in opposite directions from the slope, from which headways were opened to establish sublevels for up-dip panel mining (Southey 1969).

Submarine iron ore was recovered by both companies using the open-stope method of room-and-pillar mining from advancing down-dip sublevels. This method is particularly suited for flat-lying to subhorizonal sedimentary deposits because they are tabular with large along-strike extent. In this method, large open areas—rooms or stopes—are mined to create multiple underground cavities while leaving unmined ore as pillars to support the hanging wall (roof). Mining commenced by

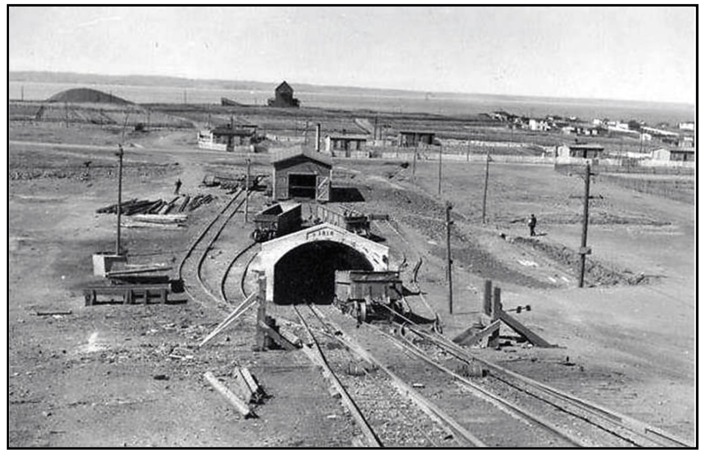

Figure 9. The adit of Scotia Company's No. 3 double slope submarine mine and No. 6 mine deck head in the distance. Source: Memorial University of Newfoundland–Digital Archives Initiative.

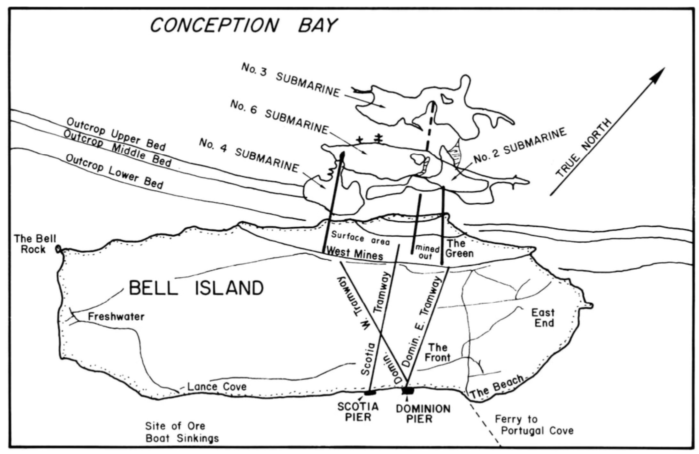

Figure 10. Map of Bell Island showing location of the submarine mines, slopes, and surface infrastructure (Anson 1951).

opening low-angle drifts on both sides of the decline at 75 m intervals in the ore beds to serve as the main headway and initial blasting face. Dimensions of the slopes, headways, and rooms varied, depending upon the thickness of the ore bed and the competency of the surrounding rock units, with the goal of minimizing artificial roof support. At No. 3 mine, rooms were spaced at 20 m centres and created by swing blasts, where there is only one free face available, and then enlarged using slabbing blasts orthogonal to the free face, which allowed the mine to open several rooms laterally from the initial drift (Fig. 11). Pillars were 6 m in diameter creating roof spans of 8 m; roof heights were the full thickness (15 m) of the ore bed. Structural requirements of the pillars limited extraction to 60%. Mining was confined to a minimum cover depth of 60 m from the back (roof) to the ocean floor, which restricted mining to a minimum of 300 m from the shoreline of the island.

Mining was organized into two shifts of workers comprising drillers and blasters in one shift, and face cleaners and shovelers in the second. A crew of two men operated a 7.6 cm percussion drill with a steel bit and drilled 12 holes in each

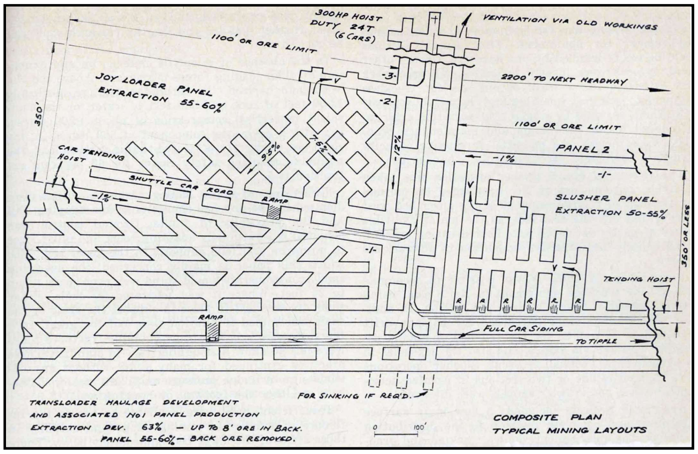

Figure 11. Composite plan of mining layout for No. 3 mine (Southey 1969).

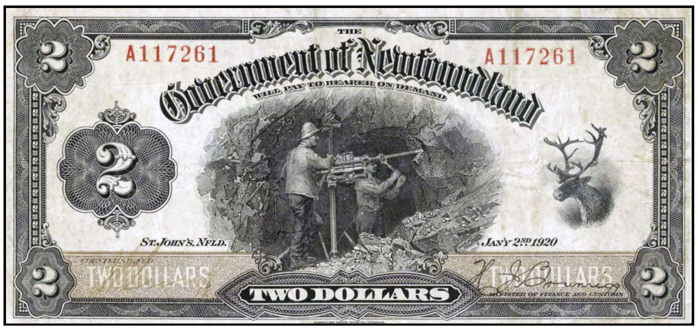

Figure 12. Dominion of Newfoundland $2 bill issued by the Department of the Treasury in 1920 featuring drillers in the submarine mines at Wabana.

room face (Fig. 12). Each of the 12 holes in the working face was filled with 3.1 kg of 50% Acadia dynamite and exploded by low-tension detonators fired from a central battery. Blasting was always conducted at night for safety due to the proximity of the working faces in relatively small rooms. Where the back height of the rooms was less than 3 m, ore was blasted in one lift, whereas rooms over this height were blasted in two lifts. Blasted ore was removed from the face, back, and walls in the room by a pair of shovelers. The men shoveled directly into 1.68 tonne trackless muck cars for transport to the headway of the hoisting slope. Each shoveler was expected to load 16 tonnes of ore in a ten-hour shift. Clydesdale draught horses were used to transport ore in shuttle cars to the base of the hoisting slope and waiting locomotives (Fig. 13). Each mine contained several subterranean stables to care for the equines. One horse in No. 6 mine is reported to have worked underground for twenty-six years (Weir 1986); although she spent her retirement years grazing on the surface of the island (Martin 1983).

After transport to the main haulage decline, ore was conveyed to the deck head at the surface via 23 tonne open mine cars on a 0.91 m gauge track, coupled in groups of seven, by 3.3 cm cable drawn by a Corliss valve hoist engine. Each mine delivered (on average) 100 cars an hour to the surface at a rate of 853.4 m/min, over a maximum distance of 3.5 km (Smallwood 1920). Once on surface, the ore was sent to a gyratory crusher and loaded into steel tram cars for transportation to

Figure 13. Clydesdale horse transporting ore underground at Wabana mines. Photo by Joseph Harvey (Martin 1983).

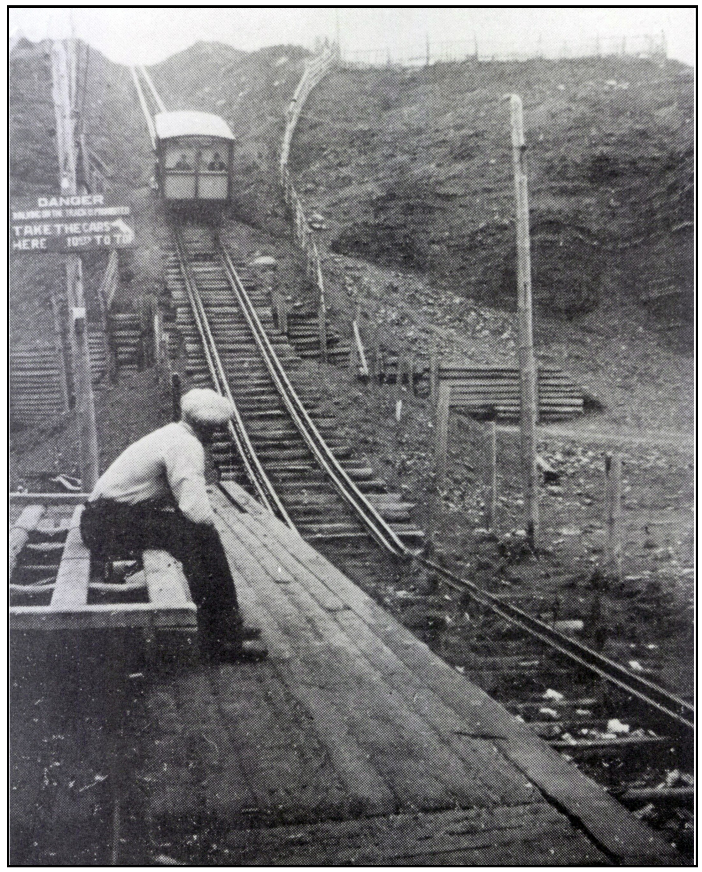

Figure 14. Cable drawn, 0.6 m (2 foot) narrow gauge tramway used to transport ore from the mine to the piers and miners from the piers to the mine adit. Source: Memorial University of Newfoundland–Digital Archives Initiative.

the loading pier on the east side of Bell Island by one of two double track tramways (Fig. 14). The tramways were up to 3 km long and consisted of 0.61 m narrow gauge track and had cars that were pulled by a 2.5 cm diameter cable powered by a condensing steam engine. The tramway operated at a cable velocity of 106 m per minute with a daily capacity maintained at 3048 tonnes.

The tramways terminated along the southeast coast of Bell Island, at two loading piers. Ore delivered at the northern Dominion Pier or southern Scotia Pier was unloaded in storage pockets located in naturally occurring ravines with a capacity of 30.4 to 40.6 thousand tonnes. From these stockpiles, ore was moved by steel link conveyer to the 23 m high, 76 m long shipping piers for loading into ore vessels at a rate of 4060 tonnes per hour (Fig. 15).

The first two decades of mining were prosperous for the Dominion and Scotia companies with annual profits for both in excess of $1 million. The start of the First World War, however, had a major negative impact on the mines. The Dominion Company, having shipped its entire production to the company's steel plant in Sydney, closed all but one of its mines and laid off 1500 workers—with some enlisting without delay in the Newfoundland Regiment to be sent to the Western Front (Martin 1983). The impact on the Scotia Company was much greater. Although the Scotia Company shipped over 508,000 tonnes of ore annually, by 1914 only a minor amount of ore was reserved for its steel plant in Nova Scotia because most of it was destined for European markets. The cessation of exports to the United Kingdom and Germany caused the Scotia Company to close all its mines until after the end of the war.

The post war worldwide recession lead to a collapse in the iron markets which forced the amalgamation of the Dominion and Scotia companies. This merger was fronted by Canadian Roy Mitchell Wolvin (1885–1945), president of Halifax Shipyards. Wolvin, backed by a syndicate of British financial interests, purchased a majority of the Dominion Company shares and began a hostile takeover of the Scotia Company which resulted in a 1921 merger to create the British Empire Steel Corporation (BESCO). The growth and profitability of BESCO stalled, however, due to the spurious issue of shares and inflated claims of BESCO's assets resulting in overcapitalization of the company. In 1922, BESCO wanted to cut production to reduce its debt and boost liquidity and negotiated in secret with the Government of Newfoundland for an agreement to keep the mines open in exchange for donations to the Liberal Reform Party election campaign. By 1925, the market valuation of BESCO dropped significantly, forcing the company to approach the Liberal-Conservative Progressive Government with a request for more concessions including the suspension all ore royalty payments for 50 years. Prime Minister Walter Monroe (1871–1952) denied the request, thus initiating the company's downfall. BESCO was unable to reorganize its corporate structure and by summer 1927 it was insolvent and its assets were then seized by the National Trust Company.

The National Trust Company operated the mines for a four-year period, which was for the most part uneventful, except for a spat with the Government of Newfoundland. National Trust refused to pay any royalties for the two-year period from 1926–1928, and in May 1929, Prime Minister Sir Richard Squires (1880–1940) ordered customs officials to seize the ore carrier SS *Boulderpool* and impound her until the company posted a bond for unpaid taxes. The following year, the National Trust Company sold its interest in all Wabana mines to the Dominion Steel and Coal Company Limited (DOSCO) of Nova Scotia, a holding company formed by former BESCO investors.

Figure 15. Dominion of Newfoundland 24-cent postage stamp of 1932 featuring the Scotia pier.

At the time DOSCO acquired the property, they announced a $6 million investment for expansion of the four non-integrated mines: No. 2, No. 3, and No. 4 in the Lower bed; and No. 6 in the Middle bed. The global economic downturn caused by the Great Depression, however, severely affected the country and caused DOSCO to close two of the mines and reduce the remaining two mines to a two-day work week. The mines traditional markets of the United Kingdom and Canada had been reduced and the increasing demand from the German market was the only reason the mines survived. Throughout the 1930s, Nazi Germany was the largest customer for Wabana iron ore—used by the industrial centers of the Ruhr to create steel for rearmament following Adolf Hitler's 1933 declaration of withdrawal from the League of Nations. By 1938, DOSCO reopened all four Wabana mines to supply the voracious German demand for iron to construct tanks, ships, submarines, and aircraft for the *Wehrmacht*. The final shipment of Germany-bound ore left Bell Island for the Port of Hamburg during the last week of August 1939, a few days before the Invasion of Poland and the outbreak of World War II.

The prosperous times for the Wabana mines continued throughout the early years of World War II. Although exports to Nazi Germany were halted, they were more than made up for by the increased demand from the United Kingdom, which was highly dependent on imported goods and material. The German blockade of the United Kingdom, an attempt to stem the flow of merchant shipping that enabled the country to sustain itself, was conducted mainly by unrestricted submarine warfare during the Battle of the Atlantic. In 1942, the U-boat threat came to Bell Island.

On 5 September 1942, two bulk carriers were loaded with ore and waiting in the Tickle off the southwest end of Bell

Island to join Convoy SC99 to Liverpool. German submarine *U-513*, under the command of *Korvettenkapitän* Rolf Ruggeberg (1907–1979), was lying in wait beneath Conception Bay and launched three torpedos that hit and sank the British ship *Saganaga*, which went down with her cargo and 30 of her crew. The Canadian bulk carrier *Lord Strathcona* was struck moments after and sank immediately. Two months later on 2 November 1942 another raid, this time by *U-518* commanded by *Kapitänleutnant* Friedrich-Wilhelm Wissmann (1915–1963), sank the Free French ship *Paris Lyon Marseille 27* and the Canadian freighter *Rose Castle* with the loss of 69 men. The U-boat fired an additional torpedo at the 3000-tonne collier *Anna T.* The torpedo missed the vessel, passed under the bow of SS *Flyingdale* and struck the Scotia pier, making Bell Island one of the few locations in North America to come under direct attack by the *Kriegsmarine* in World War II.

DOSCO's fortunes were boosted following the end of the war. The worldwide increase in demand for iron in the late 1940s was because steel was needed to help rebuild Western European economies. By 1950, long term contracts were negotiated with the United Kingdom and Germany and the mines were in full production and exporting over 1.52 million tonnes of ore per annum. DOSCO undertook a series of major expansion projects with the initial goal to double annual production to three million tonnes. Commencing in 1949, percussion steel bit drills were replaced with self-propelled dual-boom jackleg drills with tungsten carbide bits, and hand loading of ore cars by shovelers was phased out and replaced by mechanical loading using three-drum slusher hoists, electric crawler shovels (Fig. 16), and Joy cable-gathering arm loaders. Loaded cars at the mine face were transferred from the sublevel siding by single or tandem 12.2-tonne electric-cable shuttle cars to a series of tipple and jaw crushers on the main levels of all mines, except No. 2 which was closed in January 1950.

The greatest change at Wabana, however, was the mechanization of underground to surface ore transportation. Horses were replaced by underground tramways with electrically-powered locomotives coupled to two dozen 5-tonne cars. Trackless mining equipment was introduced between 1951 and 1954. In 1952, the hoist engines in the slopes were replaced by two ten-flight 0.9 m conveyer-belt systems with a capacity of 1067 tonnes per hour. The system installed in No. 3 mine extended 3.8 km from the bottom of the decline to the deck head and was the longest mine conveyer in the world at the time of installation. In 1951, the dual tramway system for ore transport was removed and replaced by roads to Scotia pier, over which a collection of 22-tonne diesel-powered, Euclid tipper trucks (Fig. 17) hauled ore. The trucks were later supplemented by a high capacity (914 tonnes per hour), 0.9 m conveyer system that transported ore from face to ship via a single belt across the island (Fig. 18). By 1957, the Scotia pier, still showing the effects of torpedo damage, was upgraded to accommodate 38,600-tonne bulk carriers and the Dominion pier was decommissioned and abandoned (Fig. 19).

Regardless of increased production, the bulk mining methods and increased ore transfers led to deterioration in product quality; the grade of direct shipped ore regularly fell below the

Figure 16. Electrically-powered mining shovel loading ore in No. 3 mine, August 1949. Photo by George Hunter. Courtesy of Library and Archives Canada (PA–4948444).

Figure 17. Road and Euclid trucks transporting ore across Bell Island in the 1950s. Source: Memorial University of Newfoundland–Digital Archives Initiative.

market requirements of 51% iron and 12% silica. To improve the grade of concentrates, a continuous float-sink heavy media separation plant was installed adjacent to the No. 3 deck head in 1955 (Fig. 20). The mill processed ore by froth flotation to remove low-grade, non-ferruginous gangue; this lowered the silica content by 1–2% with a corresponding increase in iron concentration of the processed ore (Gross 1967).

Throughout the different mines, the iron content in different ore beds, and even within the same bed, ranged from 45 to 61.5% and the silica concentration from 6.5 to 20%. As shipped ore was sold based upon a uniform minimum grade of 50% iron and maximum 14% silica, ore from the different

Figure 18. Conveyer and stockpile for ore storage adjacent to the Scotia pier. Source: Memorial University of Newfoundland–Digital Archives Initiative.

Figure 19. Abandoned Dominion pier (background), stockpile for ore storage (centre), and active Scotia pier (foreground). Source: Memorial University of Newfoundland–Digital Archives Initiative.

beds was mixed to produce a uniform grade of ore. Analysis of the average iron content of ore mined in 1965 was 48%, but after beneficiation in the flotation mill the ore shipped contained 50.18% iron, 12.92% silica, and was dry—i.e. no significant free moisture (Gross 1995).

DECLINE

The increased demand for steel after World War II caused an extensive worldwide surge in iron exploration resulting in discoveries of large deposits in Labrador, South America, and Australia. By the 1960s, the Wabana mines, now under the control of A.V. Roe Canada Limited, faced increased competition from foreign producers, who flooded the world iron market with low-cost, high-quality ore. Production decreased annually from 1958, resulting in the May 1959 closure of the No. 6 mine; it continued to decline resulting in the 1962 closure of No. 4 mine. On 19 April 1966, with the market for Wabana ore having all but disappeared, the company announced the closure of the last operating No. 3 mine.

Figure 20. No. 3 mine deck head and float-sink mill and infrastructure added during mine expansion and modernization in the late 1950s. Source: Memorial University of Newfoundland–Digital Archives Initiative.

At the time of closure on 30 June 1966, the Wabana operation was the oldest, continually producing mine in Canada. Over its seven-decade lifetime, 25% of the steel produced in Canada was manufactured from Wabana ore (Gross 1967). Production fluctuated widely through the history with an average annual production rising from over 360,000 tonnes between 1896 and 1905 to over 1,700,000 tonnes during the last decade of production (1956 to 1966). Annual production peaked in 1960 when 2,500,000 tonnes of concentrated ore were shipped. In total, over 80 million tonnes (78,989,412 long tonnes) of direct shipped and beneficiated ore were produced over the 71-year life of the mines (Sabina 1976).

The cessation of mining in 1966 was not due to exhaustion of ore reserves but rather to other factors including operating costs and the chemical and physical nature of the ore. Both are discussed below.

Submarine mining of shallow dipping ore bodies has inherent constraints that result in high operating costs: i) as extraction progresses the working faces get increasingly farther away from the deck head, which at No. 3 mine reached a maximum distance of 4 km; ii) the room and pillar method of mining leaves significant quantities (up to 40%) of ore in place; iii) submarine mines must be dammed below the high water mark and continuously pumped to prevent inundation of seawater; and iv) the shallow dip of the ore beds (< 10 degrees) precluded the use of gravity to move ore along a chute from higher to lower drift levels, requiring the use of expensive mechanical equipment to transport ore to the hoisting station. In addition, economic stagnation due to the American recession in 1958, new metallurgical processes for steelmaking that favoured a low-phosphorous ore, and competition from inexpensive (i.e. open pit and direct shipped) magnetite ore from Labrador placed the mine in a precarious economic position.

However, the leading factor that hastened the Wabana mines to obscurity was the chemical and physical nature of the ore itself. It possessed an average of 12% silica and 4.7% alumina, both of which are undesirable constituents in ore as a furnace charge for steel making. Excess silica and alumina must be separated from the ore and removed in slag by oxidation of the molten iron with lime or magnesia flux. The dissolution of silica and alumina is at least partially controlled by temperature, which necessitates higher energy requirements and longer heat times to form the slag and maintain it in a liquid state. In addition, the silica:alumina ratio is critical during steelmaking as high alumina contents (> 2%) cause an increase in slag viscosity, while excess silica results in large slag volumes.

The first industrial process for inexpensive mass production of steel was invented in 1856 by Sir Henry Bessemer (1813–1898) in Sheffield, England. The *Bessemer process* permitted the refining of large amounts of pig iron into steel by passing air through a bath of molten iron contained in a bottom-blown vessel with a lining of refractory silica and aluminium oxide-rich clay. The oxidation of impurities in the ore raises the temperature of the iron mass such that the iron stays molten from the thermal energy produced. This process is particularly suited for pig iron that has low phosphorus (< 0.045%) and high silicon (> 11%) concentrations. Most of the steel in the world in the 19th century was produced by the Bessemer process. High-phosphorous ores (> 0.18%), however, are unacceptable for the Bessemer process as the siliceous refractory lining can only react with oxides of silicon, manganese, and carbon for removal in an acidic slag. The acidic phosphorus oxides formed upon blowing air through molten iron do not react with the refractory lining and thus remain in the finished steel. The Bessemer process revolutionized steel production by decreasing its cost while greatly increasing the scale and speed of manufacture (Stoddard 2015).

The main inherent shortcomings of the Wabana ore are its high-phosphorous content (0.85–0.95%) and the fine-grained oölitic character of the mineralization that precluded physical beneficiation beyond 2%. Phosphorus, along with carbon and nitrogen, are elements that form a solid solution with iron, thereby increasing the strength of iron to form steel. The addition of minor quantities (ca. 0.1%) of phosphorus increases both the yield strength and ultimate tensile strength of low-carbon steel while also improving martensite hardening and formability. Phosphorus is also used as an alloy in austenitic stainless steel to make it easier to forge and machine, though it has a detrimental affect on corrosion resistance. The strengthening effect of phosphorus in steel, however, is accompanied by a simultaneous decrease in both ductility and impact to toughness. As a result, phosphorous is regarded as an undesirable impurity in most carbon alloy steels and is limited to a maximum concentration of 0.05%. Low phosphorus, high strength steels are essential for applications where high ductility is required such as structural steel for buildings, bridges and ships, and rolled stock for automobile parts and consumer products (Lula 1986).

The only source of phosphorus in steel is from the raw ore. Thus, evaluation of iron deposits is the preferred method to ensure the low phosphorus content conforms to the rigid specifications of the metallurgical process. Phosphate is reduced during iron smelting in a blast furnace and almost all remains in the molten pig iron and consequently must be removed by a fluxing agent in order to convert cast iron ingots into high quality steel.

Phosphorus can be removed from pig iron during steel refining by modification of the Bessemer process developed in 1877 by Sidney Gilchrist Thomas (1813–1898). Thomas utilized dolomite bricks as a magnesia-rich lining in a larger Bessemer converter charged with a lime flux for slagging. The *Thomas process,* also called the *basic Bessemer process,* produces a basic slag with high solubility of phosphorus oxide that floats to the top of the converter and is skimmed off, resulting in phosphorus-free steel. The Thomas process made possible the commercialization of cost-effective steel by refining pig iron from high-phosphorus, non-Bessemer ores like Wabana, and of the Minette ironstone deposits prevalent throughout Europe. Additionally, the molten slag was granulated in water to produce tetracalcium phosphate ($Ca_4(PO_4)_2O$), a phosphorus-rich fertilizer prized for use in agriculture.

By the start of the 20th century, the Thomas process was the most common method of steel production in Europe and Canada but the process was never fully utilized in the United States. Although the American production license for Thomas process steel was acquired by Andrew Carnegie (1835–1919), Carnegie Steel Company and its successor United States Steel Corporation, preferred the *Siemens–Martin process* which utilized an open-hearth regenerative furnace for making steel. As a result, the United States was an inconsequential and irregular market for Wabana ore, and significant steelmaking developments of high-phosphorus ironstones in the Appalachian Foreland Basin were never realized.

After World War II, the decline of open-hearth and basic Bessemer steel was hastened by enhanced changes in the operating efficiency of blast furnaces. The first commercial scale, basic oxygen furnaces utilizing top-blown pneumatic gaseous oxygen converters were introduced in 1952 in Linz and Donawitz, Austria. This process enabled steel with high chemical and thermal efficiency to be produced at a faster rate and lower price than required by both the open-hearth Siemens–Martin and Thomas processes. The market for high-phosphorus non-Bessemer Wabana ore steadily declined as the basic oxygen *Linz–Donawitz process* became the world's dominant steelmaking technology in the latter part of the 20th century because of its superior quality, high productivity and low capital costs. By 1960 the effect of the chemical properties on the market acceptance of Wabana ore forced DOSCO to examine more thorough beneficiation methods to increase market share. A research program by DOSCO metallurgists determined that a low-impurity concentrate of blast furnace pellets grading > 60% iron with 6 to 8% silica and reduced phosphorous could be produced by a sequence of autogenous grinding, high temperature magnetic roasting with steam, and acid leaching (Southey 1969). However, DOSCO's parent, Hawker Siddeley Canada, decided that the capital investment required to meet increasingly high physical and chemical specifications was too costly to be warranted considering the changing world market requirements.

RESOURCES AND RESERVES

The complexity of accurately calculating submarine mineral resources at Wabana explains why the reported estimates vary. The first estimate of resources (Howley 1910) was made by extrapolation of the ore beds to depth, resulting in an estimate of 3.2 billion tonnes of ore, although Howley did not indicate how much was recoverable. Similar estimates of 2.9 to 3.2 billion tonnes of recoverable ore were calculated independently by Ellis and Eckel who testified in the legal case for the proposed dissolution of United States Steel Corporation under

US federal antitrust laws (Hayes 1915). Higher estimates of up to 10 billion tonnes of ore are dependent on extending the area (along strike and down dip beneath Conception Bay) of the Lower bed over 180 km^2 (Hart 1929).

In 1964, proven mineable reserves were over 46 million tonnes of ore at a minimum grade of 47.5% iron and maximum 15% silica (Southey 1969). The most accurate estimate of possible iron resources in the Wabana deposits was determined by Miller (1983) using a regional geophysical mapping program. By calculating the excess mass of the deposit using residual gravity anomalies isolated from Bouguer anomalies, and using a maximum deposit area of 30 km^2 as shown by the regional gravity data, the mass of iron in place ranges from 777 million tonnes to 2.14 billion tonnes with a mean value of 1.24 billion tonnes.

ECONOMIC AND SOCIETAL IMPACT

The development of the iron mines on Bell Island contributed greatly and positively to the region's economic development by helping to diversify the island's economy into sectors other than agriculture and the fishery. Of course, the impacts of mine development, as well as its many ongoing legacies, mirror the historical boom and bust cycle that is characteristic of the industry. Although the Wabana mines helped the Dominion of Newfoundland expand from a single-product export economy, by increasing employment, income, and expenditure levels, the mines belonged to a series of foreign developers whose main aim was to fulfill the insatiable demand for minerals for export markets—and ultimately profits for foreign shareholders.

The town of Wabana owes its origin to the establishment of the iron mines around which it developed. The demographic history of Bell Island therefore provides an overall measure of economic and employment changes due to the relationship between mining operations and the number of workers. In 1891, immediately before the mines opened, the population was 701. By 1901, there were approximately 1000 men and boys employed in the mines. Yet, the population had only risen to 1320, because many workers lived in company mess shacks during the week and commuted home to other communities throughout Conception Bay on weekends. Over the next two decades Bell Island witnessed unparalleled population growth, rising to 3084 in 1911 and 4357 in 1921, with the companies providing housing for workers and their families. This boom phase is characteristic of many mining towns where construction of a company town coincides with the arrival of a labour force necessary to exploit a resource. The town of Wabana became the prominent population centre on the island and had Church of England and Roman Catholic churches in addition to 28 factory buildings, post office, secondary school, hockey rink, five general merchants and two company physicians. By 1921, Bell Island surpassed Harbour Grace as the Dominion's second largest community with a population of 4357, including 424 people directly employed in the mines. Over the following decade the urgent demand for ore by Nazi Germany caused the inshore fishery to cease to exist. As Bell Island expanded to a population of 6157 in 1935, it had a single-product export economy that was entirely dependent on the iron and steel industry.

The large and relatively fast population growth continued throughout and following World War II: in 1945 the population was 8171; by 1951 it was 10,291 with mine employment of 1882. Employment reached its peak in 1958 with 2268 workers and steadily declined following the shutdown of No. 6 mine in 1959. However, the population continued to rise and by 1961 had peaked at 12,281, with 95% directly depending on the mines (Day and Pearson 1966). When DOSCO announced the closure of the No. 3 mine in 1966, the fate of Bell Island was sealed. Shortly after 1966, the population of the community declined sharply when the miners and their families left. At this time DOSCO's coal mines and steel mill subsidiaries in Nova Scotia were also losing money and Hawker Siddeley Canada decided to close its poorly performing mines and mills, not undertake any further capital expenditures, and exit the coal and steel industry. The Canadian Government of Prime Minister Lester Pearson (1897–1972) established a federal crown corporation to acquire and manage DOSCO's coal operations and develop new economic opportunities for Cape Breton. There was, however, no such federal government intervention for Bell Island. The Government of Newfoundland under Premier Joey Smallwood (1900–1991) approached a West German consortium to salvage the mining operation but in the end all government efforts to save the iron mines were futile. By 1976, only 4824 people remained in Wabana, with many moving to work in the iron mines of western Labrador.

The Wabana mines, although based on a finite resource, did not ultimately decline like other extractive deposits that are typically exhausted; instead, the failure of mining occurred as the costs of extraction began to exceed the declining market value of the product. The 2016 population of 2146 demonstrates the dramatic downsizing that continued after 1976. Bell Island is unconnected to the provincial highway system and has had to compete with the established regional centre of the northeast Avalon Peninsula for economic development opportunities. Principal growth of Wabana occurred towards the end of a lengthy post-war boom period of resource extraction and like other single-industry resource dependent towns, is economically vulnerable to decisions made by the operating company, and subject to global competition and commodity market fluctuations. The resource dependence at Wabana, like other regions rich in natural resources, causes the paradox of plenty—where the volatility of natural resource revenue is detrimental to the long-term economic prosperity.

What will become of Bell Island? Since the closure of the last mine over five decades ago, the island has been plagued by uncertainty, especially with rumors concerning attempts by the government to diversify the economy and the island's long-term viability to exist as a commuter suburb of St. John's. Perhaps potential new (or renewed) global demographic demand and metallurgical shifts (e.g. HIsarna direct reduction process) may one day signal a future for non-Bessemer ore and make the large reserves of Wabana economic again. The Province of Newfoundland is currently the leading iron producer in Canada (Conliffe et al. 2012). Based on a past production rate at Wabana of 2 million tonnes per annum with 60% recovery—

the conservative estimate of over 2 billion tonnes of recoverable ore indicate a 600-year supply of iron that one day may contribute to a share of that production.

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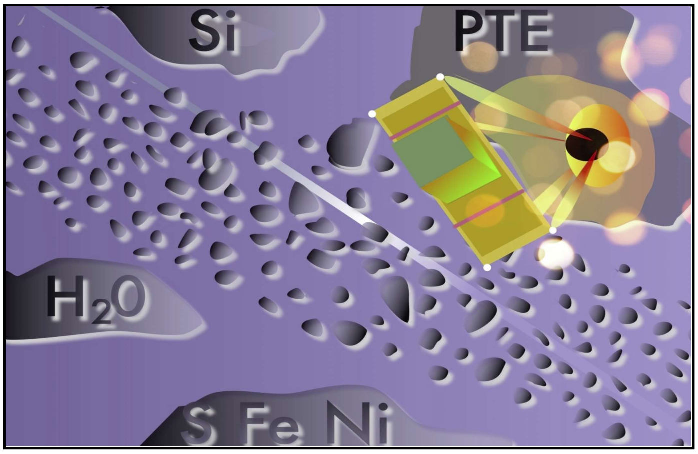

Igneous Rock Associations 24. Near-Earth Asteroid Resources: A Review

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SUMMARY

The extraction of natural resources located beyond Earth to create products can be described as space resource utilization (SRU). SRU is under active investigation in both the public and private sectors. Near-Earth asteroids (NEAs) are particularly promising early SRU targets due to their relative proximity and enrichments in two key resources: water and platinum group elements (PGEs). Water can be used to create rocket propellant, making it the only resource with significant demand given the current nascent state of the space market. Platinum group elements are valuable enough that their import to the Earth market is potentially economical, making them the other prospective resource in the current embryonic state of SRU. While it is possible to retrieve material from a NEA, doing so on an economical scale will require significant developments in areas such as autonomous robotics and propulsion technology. A parameterization accounting for asteroid size, resource concentration, and accessibility yields just seven and three potentially viable NEA targets in the known population for water and PGEs, respectively. A greater emphasis on spectral observation of asteroids is required to better inform target selection for early prospecting spacecraft. A further complication is the lack of a legal precedent for the sale of extraterrestrial resources. The Outer Space Treaty prohibits the appropriation of celestial bodies but makes no explicit reference to their resources while the U.S.A. and Luxembourg have passed legislation entitling their citizens to own and sell space resources. Whether these laws are a matter of clarification or contradiction is the matter of some debate.

RÉSUMÉ

L'extraction de ressources naturelles situées au-delà de la Terre pour créer des produits peut être décrite comme une utilisation des ressources spatiales (URS). L'URS est actuellement examinée à la fois dans les secteurs public et privé. Les astéroïdes proches de la Terre (NEA) sont des cibles URS particulièrement prometteuses en raison de leur proximité relative et de leur enrichissement en deux ressources clés : l'eau et les éléments du groupe du platine (EGP). L'eau peut être utilisée pour créer des agents de propulsion pour vaisseaux spatiaux, ce qui en fait la seule ressource pour laquelle la demande est importante compte tenu de l'émergence du marché spatial actuel. Les EGP sont suffisamment précieux pour que leur importation sur le marché terrestre soit potentiellement économique, ce qui en fait l'autre ressource potentielle étant donné l'état embryonnaire actuel de l'URS. Bien qu'il soit possible de récupérer des matériaux sur un NEA, le faire à une échelle économique nécessitera des développements importants dans des domaines tels que la robotique autonome et la technologie de propulsion. Un paramétrage tenant compte de la taille des astéroïdes, de la concentration des ressources et de l'accessibilité conduit à seulement sept et trois cibles NEA parmi la population connue, potentiellement exploitables pour l'eau et les EGP, respectivement. Il est nécessaire de mettre davantage l'accent sur l'observation spectrale des astéroïdes afin de mieux documenter la sélection des cibles pour les premiers vaisseaux prospecteurs. L'absence de précédent juridique pour la vente de ressources extraterrestres est une complication supplémentaire. Le Traité sur l'espace interdit l'appropriation des corps célestes mais ne fait aucune référence explicite à leurs ressources, tandis que les États-Unis et le Luxembourg ont adopté une législation autorisant leurs citoyens à posséder et à vendre des ressources spatiales. Que ces lois fassent l'objet de clarification ou de contradiction est sujet à débat.

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INTRODUCTION

Through centuries of scientific study and decades of space exploration, the presence of a range of potentially economic resources across the solar system has been established. Only recently has the prospect of harnessing these resources been considered a possibility. The act of harvesting, processing, and ultimately creating useful products from resources acquired in space can be described as space resource utilization (SRU). In recent years, various space agencies have been investigating one approach to SRU, namely in situ resource utilization (ISRU). As the name implies, ISRU entails using the resources encountered along the path of exploration to create products in support of the mission (Sanders and Larson 2015). SRU is not limited to the public sector. It is the opinion of some investors and industry professionals that SRU (e.g. Lewis 2014), and the hypothetical accompanying expansion of the space market, is a potentially industry-changing opportunity.

In order for SRU to be worthwhile for government space agencies, there must be a cost saving, a lowering of risk, or a mission enhancing benefit. For the private sector, profitability in a reasonably short time span following initial investment is a requisite. Considering the complexity of operations in space and the embryonic nature of the space market, this amounts to a substantial challenge. Undeterred, companies with the intentions of mining asteroids have already formed, including Planetary Resources and Deep Space Industries (recently acquired by Bradford Space). The governments of the U.S.A. and Luxembourg have demonstrated their support for SRU, passing legislation legalizing the sale of space resources (U.S. Commercial Space Launch Competitiveness Act of 2015; Government of Luxembourg 2017). While such legislation has not yet been passed in Canada, the Canada Mineral and Metals Plan, released by Natural Resources Canada in March 2019, recommends that the federal government should develop a policy approach for mining 'new frontiers' to foster investment and economic development (NRCan 2019). Space mining is explicitly acknowledged to be one of these new frontiers.

Due to their variety of resources, proximity to Earth, and attractiveness as exploration targets, previous work has identified the Moon, Mars and its satellites, and Near-Earth Asteroids (NEAs) as prime targets for SRU. The Moon is close to Earth, has various resources, and can serve as a proving ground for modern human exploration techniques prior to a human-crewed mission to Mars (e.g. Crawford 2015; Zuniga et al. 2015). SRU in the Martian system will likely be restricted to ISRU in support of Mars surface missions, and so less significant to the private sector (Mazanek et al. 2015); although SpaceX's plans for Mars transportation infrastructure include the local production of rocket fuel on the Red Planet via ISRU. Finally, NEAs, the focus of the current study, offer rich and varied resources and are accessible; ~ 20% of NEAs have one-way rendezvous travel costs lower than the Moon (Benner 2018). The range of NEA compositions includes enrichments in base metals (e.g. Fe and Ni), semiconductors (e.g. Si), platinum group elements (PGEs), and volatiles, including water, C, N and S.

The goal of this study is not to argue the superiority of NEAs as potential resource hosts rather than say the Moon (Crawford 2015). Instead, we focus on NEAs due to their importance in the near-term of SRU. As well as being accessible, NEAs are enriched in a resource vital to the early development of SRU and the space market: water. This review will first explore the nature and distribution of asteroids and their meteorite offspring, informing the incidence, abundance, and grade of asteroid resources. The following sections will then explore the logistical feasibility, legal implications, and economic viability of asteroid mining. Lastly, it will discuss current ventures and Canadian opportunities in the field.

ASTEROID CHARACTERISTICS

Asteroids are typically relatively small, rocky bodies devoid of atmospheres that orbit the Sun. They range in size from almost 1000 km to 1 m in diameter (Rubin and Grossman 2010; Burbine 2016). Very broadly, they are composed of rock, metals, and volatiles in various combinations. Asteroids are divided into populations based on their orbits and reflectance spectra. The asteroids are numerous, but their combined mass is less than that of the Moon. The mass distribution of the asteroids is also uneven, with the largest asteroid, 1 Ceres, which is also classified as a dwarf planet, making up a third of the mass of the main belt asteroids alone (Hilton 2002).

Orbital Groups

There are three main orbital groups of asteroids. The main belt asteroids (MBAs) are the largest group of asteroids. They orbit the Sun at ~ 2.2 to ~ 3.2 au (astronomical unit; 1 au is the average distance from the Sun to the Earth), between the orbits of Mars and Jupiter. The focus of this review is on the NEAs, which are those asteroids that are no farther than 1.3 au from the Sun during their closest approach along their elliptical orbits (Shoemaker et al. 1979). The NEA population is subdivided into the Amors, Apollos, Atens, and Atiras (Fig. 1) (Shoemaker et al. 1979; Di Carlo et al. 2017). The Amors orbit the Sun outside of Earth's orbit and never cross inside it. The Apollos are on average farther away from the Sun than Earth but cross into Earth's orbit from the outside. Atens have shorter orbits than Earth but cross Earth's orbit from the inside. Atiras are by far the least populous group and have shorter orbits than Earth and never cross its path.

The NEAs are more desirable for the near-term of SRU than other asteroid populations due to their relative proximity to Earth. The travel cost in space can measured in units of speed. This parameter is called ΔV (pronounced 'delta-vee'). Measured in kilometres per second, it is the change in velocity required to move from one location, or orbit, in space to another (Ross 2001). Because their orbits are so similar to Earth's, the ΔV for one-way rendezvous from Low Earth Orbit (LEO) to ~ 20% of NEAs is less than the ΔV from LEO to the Moon (Benner 2018). Another consequence of Earth-like orbits is long synodic periods, i.e. the more similar a body's orbit is to Earth's, the longer the time period between closest passes. After rendezvous via optimal trajectory, the

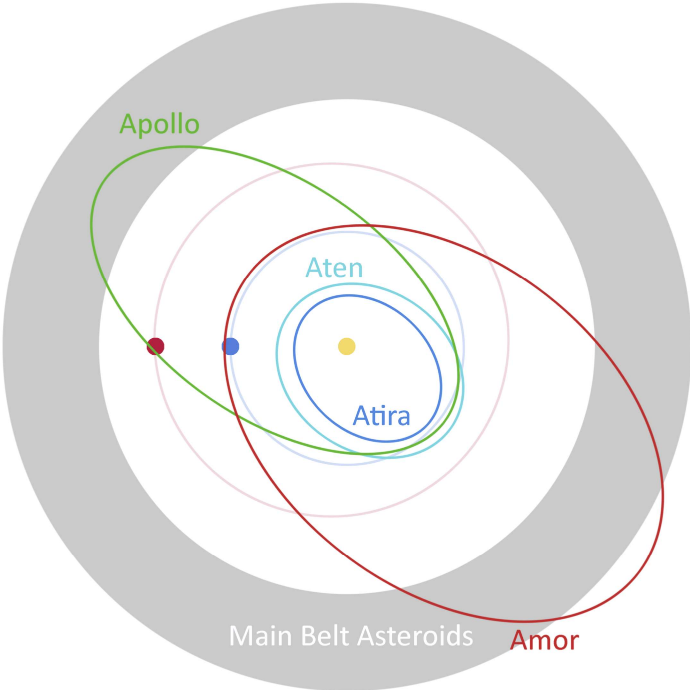

Figure 1. Near-Earth Asteroid orbital groups. The yellow, blue, and red circles designate the Sun, Earth, and Mars, respectively. The Amor asteroids have larger orbits than Earth and never cross its orbit. The Apollo asteroids have larger orbits than Earth but do cross its orbit. The Aten asteroids have smaller orbits than Earth and cross its orbit. The Atira asteroids have smaller orbits than Earth and never cross its orbit.

launch window for a minimum ΔV return trip is often many years or a decade later. Missions of shorter duration would have to budget for a non-optimal trip one way or another.

The third main family of asteroids is the Trojans. Jovian Trojan asteroids share the orbital path of Jupiter, residing in stable points ~ 60° proceeding or trailing it. These are the L4 and L5 Lagrangian points respectively. To date, astronomers have discovered over 6,000 Jovian Trojans, but some estimate Jupiter's Trojans to be as numerous as the asteroids of the main belt (Yoshida and Nakamura 2005). Other planets with at least one known Trojan are: Venus (1), Earth (1), Mars (4), Uranus (2), and Neptune (17) (Connors et al. 2011; de la Fuente Marcos and de la Fuente Marcos 2014, 2017).

Another orbital group of potential interest are the Centaurs. These bodies orbit the Sun between the orbits of Jupiter and Neptune. Although more distant than the other groups they are thought to have intermediate characteristics between asteroids and comets, a hypothesis strengthened by the detection of various ices, including water and methanol (Cruikshank et al. 1998). These bodies could be optimal for fuelling activity in the outer solar system.

Spectral Types

In addition to orbital groups, asteroids are also classified by their reflectance spectra in the visible and infrared regions of the electromagnetic spectrum. Asteroids with similar reflectance have been interpreted to possess similar surface mineralogies and, therefore, similar compositions. However,

Table 1. Asteroid Spectral Classes. Taxonomies from Tholen (1984), Bus and Binzel (2002) and DeMeo et al. (2009).

Tholen (1984)	Bus and Binzel (2002)	DeMeo et al. (2009)
C-group	**C-complex**	**C-complex**
(Carbonaceous)	**(Carbonaceous)**	**(Carbonaceous)**
B-type	B-type	B-type
C-type	C-type	C-type
F-type	Cg-type	Cb-type
G-type	Ch-type	Cg-type
	Cgh-type	Cgh-type
X-group (Metallic)	Cb-type	Ch-type
E-type		
M-type	**X-complex (Metallic)**	**X-complex (Metallic)**
P-type	X-type	X-type
	Xc-type	Xc-type
Ungrouped	Xe-type	Xe-type
S-type (Silicaceous)	Xk-type	Xk-type
A-type		Xn-type
D-type	**S-complex (Silicaceous)**	
T-type	S-type	**S-complex (Silicaceous)**
Q-type	Sa-type	S-type
R-type	Sk-type	Sa-type
V-type	Sl-type	Sq-type
	Sq-type	Sr-type
	Sr-type	Sv-type
	A-type	
	K-type	**Ungrouped**
	L-type	A-type
	Q-type	D-type
	R-type	K-type
		L-type
	Ungrouped	O-type
	T-type	Q-type
	D-type	R-type
	Ld-type	T-type
	O-type	V-type
	V-type	

factors such as the difficulty of modelling mineral absorption, regolith effects, and space-weathering, may cause objects with dissimilar mineralogies to have similar spectra and be incorrectly grouped together (Burbine 2016).

The colour of asteroids was first measured photographically by Bobrovnikoff (1929) but these measurements were too sparse and rudimentary to form the basis of a classification scheme. Chapman et al. (1975) put forth the first asteroid taxonomy and introduced the use of letters (C for carbonaceous, S for silicaceous), now a standard feature of all asteroid taxonomies. Next, Tholen (1984) proposed a new taxonomy consisting of 7 types in two groups and 7 more ungrouped types. They are the C-group (B-type, C-type, F-type, G-type), X-group (E-type, M-type, P-type), S-type, A-type, D-type, T-type, Q-type, R-type, and V-type. Like the Chapman et al. (1975) taxonomy, C-group are carbonaceous, and S-type are silicaceous or stony. The new X-group contains metallic asteroids, while the remainder have anomalous or intermediate characteristics (Table 1).

The next major overhaul of asteroid taxonomy stemmed from the Small Main-belt Asteroid Spectroscopic Survey (Bus and Binzel 2002; Burbine 2016) (Table 1). The SMASS system was designed to agree with previous classification schemes whenever possible. Thirteen of the 26 classes have single-letter names, with 12 taken from preceding taxonomies (A, B, C, D, K, O, Q, R, S, T, V, and X) and one new class (L). The remaining 13 classes have lowercase modifiers to denote asteroids with intermediate spectral qualities. All but five of the classes are sorted into one of three complexes, broadly consistent with Tholen's groups. The taxonomy is as follows: C-complex (B-type, C-type, Cg-type, Ch-type, Cgh-type, Cb-type), S-complex (S-type, Sa-type, Sk-type, Sl-type, Sq-type, Sr-type and endmembers A-type, K-type, L-type, Q-type, R-type), X-complex (X-type, Xc-type, Xe-type, Xk-type), T-type, D-type, Ld-type, O-type, and V-type (Bus and Binzel 2002). The C, S, and X designations have the same meaning as in Tholen (1984).

The most recent iteration is the Bus-DeMeo taxonomy (DeMeo et al. 2009), which comprises 24 classes with a 25th Xn class being added after publication of the original paper (Burbine 2016). The class designations are nearly identical to those of Bus and Binzel (2002); only the Ld, Sl, and Sk classes were removed while the Sv and Xn classes were added (Table 1). Most bodies measured in both studies retained their classification. Those that did change mostly belonged to the S-complex subclasses (DeMeo et al. 2009). This taxonomy uses a 'w' at the end of certain classes to signify that the body has experienced space weathering. The taxonomy is as follows: C-complex (B-type, C-type, Cb-type, Cg-type, Cgh-type, Ch-type), S-complex (S-type, Sa-type, Sq-type, Sr-type, Sv-type), X-complex (X-type, Xc-type, Xe-type, Xk-type, Xn-type), A-type, D-type, K-type, L-type, O-type, Q-type, R-type, T-type and V-type (DeMeo et al. 2009).

Spectral Class Distribution

The differences in the mean albedo of asteroid spectral classes introduces discovery bias into the population of observed asteroids. Spectral classes with high average albedo (e.g. S-complex) are more readily discovered for a given diameter than asteroids with lower albedo (e.g. C-complex) (Fig. 2). The number of NEAs with spectral types is very low compared to the number of known NEAs (Carry et al. 2016). Thus, when considering the resource potential of the NEAs as a population, it is helpful to consider the debiased distribution, while bearing in mind that spectral data must be available for a specific asteroid for it to be considered as a potential mining target. Stuart and Binzel (2004) provide a bias-corrected distribution of spectral classes for NEAs by using a methodology that combines spectral and albedo data sets.

METEORITES AS ANALOGUES

Since no space agency has yet managed a sample return of more than a few micrograms of an asteroid (i.e. the Hayabusa mission), meteorites are the main samples of asteroid material currently available for study. However, the lack of spatial resolution and the aforementioned difficulties in interpreting asteroid spectra make meteorite–asteroid comparisons difficult, complicating the study of asteroid geology. Nevertheless, in the near-term, meteorites remain the best and only physical samples of asteroids available to scientists.

Meteorite Taxonomy

Meteorites are classified into chemical groups, each containing

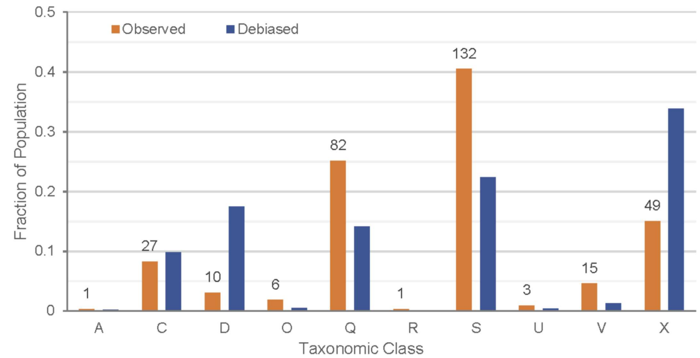

Figure 2. Observed and debiased distribution of taxonomic classes in the Near-Earth Asteroid (NEA) population. Observed data (n = 326) are from JPL Small-Body Database (accessed 05/06/18). For asteroids with both Tholen (1984) and Bus and Binzel (2002) classifications the latter took precedence. Some spectral classes were combined in accordance with the debiased estimations from Stuart and Binzel (2004). The numbers at the end of the orange columns are the total number of NEAs of that class in JPL Small Body Database.

rocks interpreted to be from a single parent body. The ultimate goal of meteorite classification is to couple each chemical group to its parent body in space. This goal has thus far proven elusive. The howardite-eucrite-diogenite (HED) clan of meteorites, thought to originate from the crust of asteroid 4 Vesta, is the only group of meteorites correlated with a specific asteroidal parent body (e.g. Consolmagno and Drake 1977). Except for a small number derived from the Moon and Mars, the majority of meteorites are derived from asteroids (Weisberg et al. 2006).

Traditionally, meteorites were divided into three categories based on composition alone: stony, stony-iron, and iron (Weisberg et al. 2006). Modern taxonomies incorporate their chemical, isotopic, compositional, and petrological nature to group samples that are genetically related (Weisberg et al. 2006). The first distinction made is the degree of differentiation of the parent body. Meteorites from undifferentiated bodies are called chondrites, named for the small (1–2 mm) silicate spheres called chondrules that they often, but do not necessarily, contain (Weisberg et al. 2006). Meteorites from differentiated bodies are called achondrites, primitive achondrites, or nonchondrites, depending on the taxonomy, and can be texturally altered but chemically primitive, partially melted, or fully differentiated. The literature contains numerous taxonomies that demonstrate no consensus on classification hierarchy, except for the final distinction of chemical group. For example, a particular specimen will belong to the same chemical group in all schemes, say an IIIAB iron, but that group could be deemed to be either a differentiated nonchondrite or an achondrite. For a thorough review of the subject the reader is referred to Weisberg et al. (2006).

Geological Processes

The geology of meteorites reflect geological processes that operated on the asteroid parent bodies. Such processes are responsible for the distribution of resources on asteroids. Perhaps most obvious is differentiation, with iron meteorites interpreted as representing core material and other meteorite classes, such as HEDs, representing crustal material (e.g.

Hutchison 2007; Elkins-Tanton and Weiss 2017). Chondrites show evidence of more localized processes, including thermal metamorphism, aqueous alteration, and shock metamorphism. Thermal metamorphism of increasing grade homogenizes the chemical composition of minerals, coarsens mineral grains at the expense of the matrix, before finally forming new minerals (Hutchison 2007). The parent bodies of meteorites displaying aqueous alteration warmed during accretion, but not enough to initiate thermal metamorphism. High water contents obtained from the solar nebula combined with this gentle heating led to the alteration of much of the olivine and pyroxene into hydrous phases in many meteorite classes (e.g. Hutchison 2007). This process created some of the most desirable asteroid classes from a resource perspective.

ASTEROID RESOURCES

Through asteroid spectroscopy and the study of meteorites, we know that asteroids contain a diverse array of resources including water (in hydrated minerals and ice), base metals, semiconductors, PGEs, and volatiles. For an asteroid resource to be considered for SRU, however, it must demonstrate mission enhancing or profit earning potential. A large part of the motivation for SRU is the potential cost savings of garnering resources required in space in situ. The additional expense associated with acquiring resources in space must be offset by the cost savings of reduced launch mass. With rocket launches out of the equation, the most cost-effective means of meeting demand on Earth will remain mining the planet itself. It follows that for any resource to be considered for SRU, at least in the short- to medium-term, there must be demand for it in space. Currently, the only resource with significant demand in space is water. A possible exception to this rule is the PGEs. They are sufficiently valuable that their import to Earth could be potentially economical in the future. Below, we discuss the short- and long-term potential of SRU from NEAs.

The Short Term

Excluding the engineering cost of extracting a target resource from an individual asteroid, the viability of an asteroid as a mining target is a function of its value and accessibility. An asteroid's value can be estimated as the product of its volume, density, concentration of the desired resource, and value of that resource. Its accessibility can be quantified as the minimum ΔV required for spacecraft rendezvous from LEO. For the purpose of the following parameterization, the minimum value that an asteroid must have to be considered a viable target will be set at $1B, approximately the cost of an average interplanetary space exploration mission, and not far off the capital expenditure required to start a large mine on Earth.

Platinum Group Elements

PGEs are highly valued due to their scarcity, usefulness as catalysts, resistance to corrosion, and high melting points (Zientek and Loferski 2014). Except for the less valuable element, Ru, each element was valued between $12,800 and $35,600 USD kg^{-1} ($400 to $1,100 USD/troy ounce) on average in 2017 (https://apps.catalysts.basf.com/apps/eibprices/mp). These values are high enough that they may allow for economic extraction of PGEs from asteroids for the Earth market. The scarcity of PGEs is driven by their highly siderophile nature. During Earth's differentiation they partitioned strongly into the core, leaving the crust and mantle extremely depleted (McDonough and Sun 1995). What little PGEs that are found outside of the core are possibly the product of a late chondritic veneer (e.g. Schmidt 2004). Like Earth, some asteroids are also differentiated. Subsequent collisions have fragmented some of these bodies, thereby exposing their PGE-enriched core material. These are the metallic X-complex asteroids, thought to be largely composed of FeNi alloy, and are the likely parent bodies of iron meteorites (Burbine 2016).

The literature contains limited data on the full suite of PGE concentration in iron meteorites. Iridium concentrations are well studied, however, as they are used in iron meteorite taxonomy (Scott et al. 1973). For iron meteorites in general, PGE occurrence can be estimated as totaling seven times Ir abundance in CI chondritic ratios (Elvis 2014). A group of 71 iron meteorites from various chemical groups compiled in two papers have a mean concentration of 27 $\mu g\ g^{-1}$ total PGE (Wasson et al. 1989, 1998). Meteorites enriched in the 50th and 90th percentiles in the distribution contain 14 $\mu g\ g^{-1}$ and 68 $\mu g\ g^{-1}$ of PGEs respectively.

Asteroids are too small to be spatially resolved by ground-based telescopes. Instead, telescopic observations provide apparent magnitude (h), which is the brightness of an object as perceived by an observer on Earth. Apparent magnitude can then be used to calculate absolute magnitude (H), which is the brightness of an object as it would be seen from a standard distance. From H, and an assumed average albedo for NEAs of 0.14, asteroid diameter is calculated. Lastly, volume is determined assuming a spherical shape. While virtually all asteroids are not spherical, this assumption is made considering that the diameter calculated will be intermediate between the asteroid's long and short axes, resulting in a reasonable approximation of asteroid volume. There appears to be no correlation between absolute magnitude (H) and taxonomic class in the NEA population (Stuart and Binzel 2004); i.e. taxonomic classes are uniformly dispersed throughout the size range of NEAs.

The density of metallic asteroids remains poorly constrained. Iron meteorites have densities of ~ 7900 kg m^{-3} but asteroids, particularly those of small mass (< ~ 10^{20} kg), are expected to have significant porosity (Henderson and Perry 1954; Carry 2012). Only considering asteroid densities of reasonable accuracy, and those from X-complex subclasses with densities indicative of metallic composition (Xc and Xk, ϱ_{50} from Table 3 in Carry 2012), yields a mean density of 4 000 kg m^{-3} for 12 asteroids.

'Average' (50th percentile PGE concentration) and 'good' (90th percentile) metallic asteroids reach values of $1B at diameters of 119 m and 71 m respectively. As volume and, therefore, mass scales with the cube of the radius, asteroids of increasing size rapidly increase in value. A 240 m diameter asteroid would be worth $8.2B and $39B in the average and good cases, respectively (Table 2). Accordingly, asteroids lose their value with decreasing size just as rapidly. Asteroids of 100

http://www.dx.doi.org/10.12789/geocanj.2019.46.147

Table 2. Value of Platinum Group Elements (PGEs) in metallic asteroids.

Diameter (m)	Mass (kg)	PGE Concentration (ppm)	PGE Value ($ / kg)	Value of asteroid ($M)
100	2.09E+09	14.28	19,903	$595
120	3.62E+09	14.28	19,903	$1,029
160	8.58E+09	14.28	19,903	$2,438
240	2.90E+10	14.28	19,903	$8,229
60	4.52E+08	67.66	19,903	$609
75	8.84E+08	67.66	19,903	$1,190
120	3.62E+09	67.66	19,903	$4,874
240	2.90E+10	67.66	19,904	$38,989

and 60 m diameter are only worth ~ $0.6B in the average and good cases, insufficient to warrant a mining venture (Table 2).

Of the 326 asteroids with a spectral classification in the JPL Small-Body Database, 15% (n = 49) are X-complex. This is a small fraction of the total known NEA population and does not account for discovery bias favouring higher albedo asteroids, particularly S-complex, over the lower albedo C and X-complexes (Stuart and Binzel 2004). The debiased depiction of the taxonomic distribution of NEAs of Stuart and Binzel (2004) indicate that 34% of NEAs belong to the X-complex. Due to the paucity of spectral type designations among known NEAs, the debiased fraction will be used for subsequent inferences made in this section.

Neeley et al. (2014) compared infrared and visible observations of 29 X-complex asteroids to meteorite spectra. They mainly targeted Xc- and Xk-types, as they are devoid of any strong spectral features, indicative of FeNi metal. Eighteen of the asteroids also had radar data available. Of these, 22% (n = 4) were determined to be analogous to iron meteorites by both the radar data and at least one of the two methods employing spectral data (Neeley et al. 2014). In the paper that introduced their taxonomy, DeMeo et al. (2009) classified 32 X-complex asteroids of which 66% (n = 21) were either Xc- or Xk-type.

In summary, the fraction of X-complex NEAs is 0.34, the fraction of X-complex asteroids that are Xc- or Xk-type is 0.66, and the fraction of Xc- and Xk- types that are metallic is 0.22. The product of these numbers reveals ~ 5% of NEAs are expected to be metallic. As mining missions will require heavy payloads both to and from the asteroid, targets with low ΔV are prioritized. Elvis (2014) suggests a maximum ΔV of 4.5 km s^{-1} for the accessibility cut off, as this figure at least doubles the payload capacity versus a mission to a median NEA (6.65 km s^{-1}). Only 1.4% of the 17,607 NEAs have ΔV ≤ 4.5 km s^{-1} (Benner 2018).

Adapting the approach taken by Elvis (2014), the fraction of NEAs that are expected to be prospective PGE sources is

$$P_{NEA\text{-}PGE} = P_{type}\, P_{cnct}\, P_{\Delta V}, \quad \text{(Eq. 1)}$$
$$= 0.05 \;\; 0.50 \;\; 0.014,$$
$$= 0.00035$$

where P_{type} is the fraction of metallic asteroids, P_{cnct} is the fraction of asteroids with favourable PGE concentrations (in this case 50th percentile or better), and $P_{\Delta V}$ is the fraction of accessible asteroids. By this metric, 0.035%, or approximately 1 out of every 2900 NEAs are prospective for PGEs. Using an assumed average albedo of 0.14, the number of known NEAs with D ≥ 119 m is 907 (CNEOS 2018). The product of these numbers reveals that three members of the known NEA catalogue are expected to be potentially viable PGE sources. While this may seem bleak, it is mostly limited by the stringent ΔV requirement. If propulsion technology advances enough to facilitate missions with ΔV ≤ 5.5 km s^{-1}, the number of prospective asteroids increases to 25 (~ 1/350).

These estimates are based on the currently known fraction of the NEA population (Fig. 3). The size distribution of the entire NEA population can be estimated by a simple power law (Stokes et al. 2003). The function is

$$N(> D(km)) = 942D^{2.354} \quad \text{(Eq. 2)}$$

where N is the cumulative number of NEAs above a given diameter D. From the power law there are expected to be 141,323 NEAs with $D \geq 119$ m. This increases the number of prospective NEAs for PGEs to 49 at ΔV ≤ 4.5 km s^{-1} and 403 at ΔV ≤ 5.5 km s^{-1}.

An important consideration is the effect of increased supply on PGE value. An estimated 560,000 kg of PGEs were produced from mined and recycled sources globally in 2016 (NRCan 2018). A $1B asteroid contains 50,200 kg PGEs. While price does not scale linearly with supply, adding 10% to the global supply would likely depress the price to some extent. A $10B asteroid would contain nearly the entire annual PGE production, depressing prices even further. This effect is possibly alleviated by selling asteroid derived PGEs over an extended time span.

Table 3. Value of water in C-complex Near-Earth Asteroids.

Diameter (m)	Mass (kg)	Water Concentration (wt %)	Water Value ($ / kg)	Value of asteroid ($M)
8	3.78E+05	16	5000	$302
12	1.28E+06	16	5000	$1,021
16	3.02E+06	16	5000	$2,419
50	9.23E+07	16	5000	$73,827

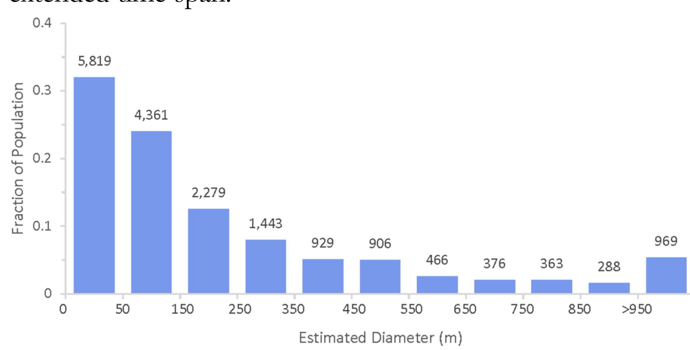

Figure 3. Size distribution of known Near-Earth Asteroids (NEA). Diameter estimates are calculated from absolute magnitude (H) using an assumed average albedo (a) of 0.14. Absolute magnitudes are from JPL Small Body Browser, current as of 21/05/18. The number of NEAs in each bin is labeled on the end of the columns.

The above estimates do not account for the engineering cost of PGE extraction. While this is difficult to directly estimate, the value per tonne of asteroid material compared to ores on Earth can shed light on the potential extraction budget. Earth's highest-grade PGE ores are located within the Stillwater Complex, Montana. The most enriched zone of the complex is the J-M reef. A 5.5 km long and 2.1 m thick section of this zone contains PGE values of ~ \$550 USD/t in Pt and Pd (Todd et al. 1982). The reserves here are small relative to South Africa's Bushveld Complex, the world's largest producer. The South African ore was worth ~ \$100 USD/t in Pt, Pd, Rh, Ru, Ir, and Au in 2015 (Thormann et al. 2017). In contrast, 50^{th} and 90^{th} percentile metallic asteroids would be worth ~ \$280 USD/t and ~ \$1350 USD/t, respectively.

Considering the relative grades and the increased complexity of space-based PGE extraction, the engineering costs may dictate that only highly concentrated metallic asteroids can be considered as mining targets, or that PGE production from asteroids will only be economical as a by-product of another process. The logistical feasibility of PGE production from NEAs is explored in the following section.

Water

Unlike PGEs, water is a strategic resource in the short term of NEA SRU due to its existing demand in space. To be economical, water must be more cost-effective to source and process it from NEAs than launch it from Earth. The value of water in space is derived from its vast array of potential applications. Most importantly in the short term, it can be electrolyzed into its constituent hydrogen and oxygen, which upon recombination create an exothermic reaction that can be harnessed for rocket propulsion. It can also be used for radiation shielding, growing plants, for breathing (O_2 from electrolysis) and, of course, drinking for humans. Presently, the market for water in space is delivery to the International Space Station and as propellant for satellite station-keeping (Sommariva 2015). In the near future, the advent of a cis-lunar (located in between Earth and the Moon) propellant depot and a fleet of satellite-servicing space-tug vehicles could considerably increase demand (Metzger 2016). A cis-lunar propellant depot would reduce costs faced by government agencies and private companies, lowering the barrier to entry for space operations, and stimulating activity in the space market. Space-tug vehicles, operated independently or by the asteroid mining corporations themselves, could rapidly transport satellites from LEO to geostationary orbit (GEO), saving satellite operators from lost profits accrued over the months it takes to deploy communications satellites via ion propulsion (Metzger 2016).

Moving forward, an important potential application of water in space is for radiation shielding. Of the types of radiation prevalent beyond Earth's magnetosphere, galactic cosmic rays and solar particle events pose the greatest risk to human health (Cucinotta and Durante 2006). Together, they are the source of all cosmic radiation (Sihver 2008). Unlike other forms of radiation (e.g. gamma rays) cosmic rays are not most effectively shielded by dense, high atomic mass materials (Sihver 2008). Their interaction with these materials produces secondary radiation, in some cases to the effect of increasing the total intensity. Liquid hydrogen is the most effective shield against cosmic radiation, with low atomic mass hydrogen-bearing compounds, such as water, also performing well (Sihver 2008). Water is much simpler to store than liquid hydrogen, and large reservoirs would be required for hydration at any rate, making it the logical choice for radiation shielding.

As was the case for PGEs, the portion of asteroids prospective for water extraction can be estimated using the methods of Elvis (2014). Water is expected to be found in the highest concentrations on C-complex asteroids (Ross 2001), in hydrated phyllosilicates and in subsurface ice. Accounting for discovery bias, 9.8% of NEAs are estimated to be C-complex (Stuart and Binzel 2004).

The contribution of hydrated phyllosilicates to the water content of C-complex asteroids can be estimated from knowledge of meteorites. A study by Jarosewich (1990) compiled chemical analyses determining water content in 22 carbonaceous chondrite samples. Removing the duplicate analyses (three measurements of Murchison and the pair of ALH 83100 and ALH 83102) leaves 19 chondrites with a mean water content of 3.9 wt.%. Eleven of these have < 2 wt.% H_2O (~58%) and six (32%) have > 6 wt.% H_2O (Jarosewich 1990). This higher group will be considered the portion of C-complex NEAs enriched in water. Elvis (2014) used 10 wt.% H_2O as the contribution of hydrated phyllosilicates to the water content of C-complex asteroids. However, given it is unlikely that all the H_2O can be extracted, the current study will use this more conservative value of 6 wt.%.

The contribution of subsurface ice to the total water content is harder to estimate. Carbonaceous chondrites have porosities of 1–20% while C-complex NEAs have macro-scale porosities of 28–60% (Carry 2012; Elvis 2014). This leaves large volumes to be potentially occupied by water ice and other volatiles, but without prospecting spacecraft it is impossible to know the contents of the voids. Elvis (2014) estimated 10 wt.% H_2O as subsurface ice, a value which shall also be used in the current study.

The fraction of NEAs prospective for water is then

$$P_{NEAWater} = P_{type}\ P_{cnct}\ P_{\perp V}, \quad \text{(Eq. 3)}$$
$$= 0.098 \ \ 0.32 \ \ 0.014,$$
$$= 0.00044$$

when using the same accessibility cut off as before. This is equivalent to about1 in 2300 NEAs. Carry (2012) gives reasonably accurate densities for 19 C-complex asteroids with a mean density of 1410 kg m^{-3} (ϱ_{50}, Table 3 in Carry 2012). If water can be sold in space for \$5000 kg^{-1}, half of the historical cost of launching a kilogram of mass into LEO, a NEA as small as 12 m is worth over \$1B (Table 3). There are 17,371 known NEAs of D > 12 m for a total of seven NEAs prospective for water (Fig. 3). Increasing the minimum ΔV by 1 km s^{-1} brings the total to 62 NEAs. The validity of the figure selected for the value of water in space is discussed in the following section.

There are expected to be vastly more NEAs of small size (< 50 m) than currently known (Fig. 3). There are 4991 known

Table 4. Resources in asteroids, adapted from Sanchez and McInnes (2013).

Resource	Asteroid Class	Fraction of NEA swarm	Resource mass fraction	Space-based application	Resource mass in 120 m asteroid (t)
Fe, Ni, Co	metallic X-complex[1]	0.05	95 wt %[3]	Infrastructure material	3,438,156
PGEs	metallic X-complex[1]	0.05	68 ppm	Import to Earth, electronics	245
Semiconductors	metallic X-complex[1]	0.05	1,600 ppm[4]	Electronics (e.g. solar panels)	5,791
H_2O	water-rich C-complex	0.03	16 wt %	Propellant, radiation shielding, hydration, hygiene, respiration (O_2 - electrolysis), space resource refinement, agriculture	255,147
N_2	C-complex	0.10[2]	934 ppm[5]	Atmosphere, fertilizer	1,192
Silicates	S-complex	0.22[2]	70 wt %[6]	Agriculture, radiation shielding	1,710,030
Organics	C-complex	0.10[2]	4,000 ppm[7]	Agriculture	5,103

Resources are listed with their asteroid class of highest concentration but may be found in other classes as well. Organics refers to organic molecules only, bulk C content is expected to be considerably higher. Fraction of Near-Earth Asteroid (NEA) swarm and resource mass fraction are from the text unless otherwise noted. [1]Based on iron meteorites with 90th percentile Ir enrichment; [2](Stuart and Binzel 2004); [3](Wasson 1974); [4](Kargel 1994; Ross 2001); [5](Alexander et al. 2012; average of CM chondrites from the supplementary material); [6](McSween et al. 1991); [7](Botta and Bada 2002).

NEAs 12–50 m in diameter, but from the power law there are expected to be 3×10^7 NEAs in this size range. This brings the total number of NEAs prospective for water to ~ 13,000 at $\Delta V \leq 4.5$ km s^{-1} (Stokes et al. 2003).

Another possible reservoir of water on asteroids is surficial water ice. It is expected to be rare on asteroids due to the rate of sublimation close to the Sun but it has been detected independently by two teams on asteroid 24 Themis (Campins et al. 2010; Rivkin and Emery 2010). Ceres, a C-complex asteroid and the solar system's largest, is one of two targets of NASA's Dawn mission. Dawn began orbiting Ceres in March 2015 and continued to do so until November 1, 2018. In this time, it generated global maps using its framing camera and visible and infrared mapping spectrometer as well as gathered elemental data with its Gamma Ray and Neutron Detector. From these data it has been estimated that Ceres contains ~ 17–30 wt.% H_2O, has rare surface water ice, and that ice has remained within a metre of the surface for the body's lifetime (Prettyman et al. 2017).

The Long Term

As time progresses, the maturation of SRU and the cis-lunar economy will allow for increasingly diverse ventures. The array of resources available in asteroids could potentially permit opportunities including more ambitious and frequent space exploration missions, space tourism, and possibly a permanent human presence in space. Key resources for this level of development include base metals, semiconductors, and life-sustaining volatiles (Table 4). Sourcing and manipulating base metals such as iron in space would permit the fabrication of infrastructure at scales unhindered by the need to escape Earth's gravity well. Semiconductors are ubiquitous in modern electronics and their presence in asteroids would allow the fabrication of electronics in space. A promising application is to build enormous solar panel arrays in orbit (e.g. Glaser 1977; Sanchez and McInnes 2013). Here, the collection of energy is independent of weather conditions and the scale of the array is not limited by the need for the structure to support its own weight. The energy collected can be used in space or perhaps even transmitted back to Earth (Glaser 1977). Asteroids also contain volatile elements like C, N, P, and S, all of which are required by human metabolism. Nitrogen is particularly important because it is needed as an inert atmospheric component as well as a source of nutrition.

LOGISTICS

The logistical challenges of asteroid mining are varied, complex, and often without precedent. This section will illustrate the stages involved in asteroid mining from initial discovery to final product. Proven technologies and methods will be presented when possible, although many aspects of this section will be speculative in nature.

Many logistical specifics will change on a case by case basis depending on factors such as mission architecture, target resource, target asteroid, etc., but the process can be broadly divided into three major categories: 1) Discovery and Characterization; 2) Harvesting and Transportation; and 3) Extraction (Fig. 4). The first phase, Discovery and Characterization, describes the progression from asteroid discovery to target selection. Next, Harvesting and Transportation, deals with the retrieval and relocation of asteroid material. The final phase, Extraction, describes a collection of processes used to make finished products from raw asteroid material. The phases are presented as such for ease of communication but in practice

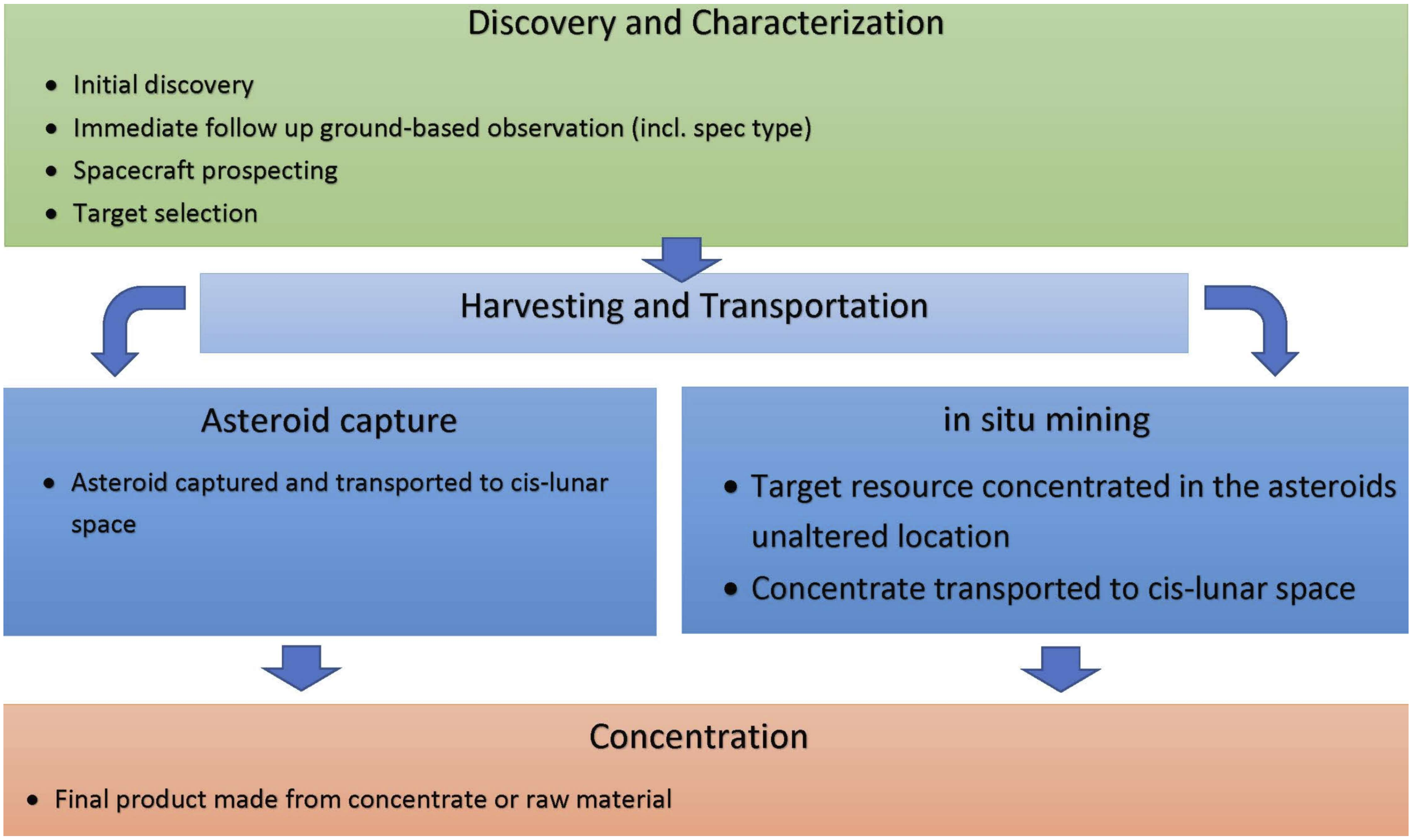

Figure 4. Stages of asteroid mining logistics. See text for details.

the boundaries between them, particularly the final two phases, will likely not be so clear-cut.

Discovery and Characterization

NEAs are continually discovered and catalogued by numerous organizations for reasons of scientific interest and as an attempt to identify potentially Earth impacting bodies. NASA's Jet Propulsion Laboratory (JPL) runs the Center for Near Earth Object Studies (CNEOS), which supports many discovery surveys at institutions throughout the United States. The five NASA-supported surveys that discovered at least a single new NEO in 2017 are the Catalina Sky Survey (991; Tucson, Arizona), Pan-STARRS1 (893; Maui, Hawaii), ATLAS (98; Hawaii), LINEAR (22; Socorro, New Mexico), and NEO-WISE (26; spacecraft in polar orbit) (CNEOS 2018). Of the 18,000+ known NEOs only 107 are comets. NEOs are discovered by taking telescopic photographs of the same area of the night sky several minutes apart (Steel 2001). Distant stars and galaxies remain in the same relative location in the photographs, but nearby objects do not (Wainscoat et al. 2016).

After ground-based observation provides a robust catalogue of NEA characteristics (size, orbital elements, spectral type) prospecting spacecraft will be deployed to the most promising asteroids to finely characterize them before the investment of a full-scale mining mission is made. There is precedent for spacecraft observation of asteroids. Including NASA's Dawn mission, there are 12 past or ongoing missions visiting 14 asteroids with five more in the planning or concept stage (Table 5). Current spacecraft asteroid observations total 3 NEAs and 11 main-belt asteroids. Even with NASA and JAXA's growing interest in asteroid missions, the scale of space borne asteroid observations required for efficient prospecting requires hands-on solutions from the would-be asteroid miner.

The spacecraft will take measurements of size and shape, density, structure, composition, and resource distribution. This can be accomplished with on-board sensors including cameras and spectrometers. These spacecraft may also include assay probes to directly sample the surface/shallow subsurface of promising regions. A single spacecraft will have to be deployed for each potential target, dictating lightweight and inexpensive design to enable multiple simultaneous deployments from a single launch vehicle.

Since only 1 in ~ 2900 and 1 in ~ 2300 NEAs are potential PGE and water sources respectively, and the prospect deploying thousands of space probes is clearly unfeasible, the need for enhanced ground-based characterization of NEAs with an emphasis on spectral class determination and small body discovery (for water-bearing NEAs) is very apparent.

Harvesting and Transportation

The two aspects of this phase are grouped together in acknowledgement of variable mission architectures and despite their different technological requirements. The first

Table 5. Successful and forthcoming asteroid exploration missions.

Mission Status	Mission Name	Agency	Launch Date	Completion Date	Asteroid Target(s)	Mission Type
Complete	Galileo[1]	NASA	18-Oct-89	21-Sep-03	Gaspra, Ida	both Flyby
	NEAR - Shoemaker[2]	NASA	17-Feb-96	28-Feb-01	Mathilde, *Eros*	Flyby, Orbit
	Cassini[3]	NASA/ESA	15-Oct-97	15-Sep-17	Masursky	Flyby
	Deep Space 1[4]	NASA	24-Oct-98	18-Dec-01	Braille	Flyby
	Stardust[5]	NASA	07-Feb-99	15-Jan-06	Annefrank	Flyby
	Hayabusa[6]	ISAS (now part of JAXA)	09-May-03	13-Jun-10	*Itokawa*	Orbit/Sample return
	Rosetta[7]	ESA	02-Mar-04	30-Sep-16	Šteins, Lutetia	both Flyby
Ongoing	New Horizons[8]	NASA	19-Jan-06	2038	APL	Flyby
	Dawn[9]	NASA	27-Sep-07	late 2018	Vesta, Ceres	both Orbit
	Chang'e 2[10]	CNSA	01-Oct-10	2029	*Toutatis*	Flyby
	Hayabusa2[11]	JAXA	03-Dec-14	01-Dec-20	*Ryugu*	Orbit/Sample return
	OSIRIS-REx[12]	NASA	08-Sep-16	24-Sep-23	*Bennu*	Orbit/Sample return
Planned	**NEA Scout**[13]	NASA	15-Dec-19	2023	*1991 VG*	Flyby
	Lucy[14]	NASA	Oct-21	2033+	Eurybates, Polymele, Leucus, Orus, Patroclus, Donald-johanson	all Flyby
	DESTINY+[15]	JAXA	2022	2026+	*Phaethon*	Flyby
	Psyche[16]	NASA	2022	arrive 2026	Psyche	Orbit
	AIDA[17]	NASA/ESA	2021 and 2023	arrive 2022 and 2026	*Didymos*	Impact and Orbit

Missions with titles in bold have asteroids for primary targets. Asteroid names in italics are near-Earth asteroids, main belt is in normal text, and trojans are underlined. All dates 2018 and onwards are projected and subject to change. Completion dates for Stardust and Hayabusa are the dates of sample cannister reentry. [1](JPL 2018a); [2](NASA 2018b); [3](JPL 2018b); [4](JPL 2018c); [5](JPL 2018d); [6](JPL 2018e); [7](ESA 2018a); [8](JHU/APL 2006); [9](JPL 2018f); [10](ESA 2018b); [11](JAXA 2018); [12](NASA 2018a); [13](Mahoney 2018); [14](Garner 2017); [15](Kruger 2017); [16](JPL 2018g); [17](ESA 2018c).

decision of this phase is the extent to which material will be concentrated prior to transport. Previous authors have suggested two approaches; "asteroid capture" and "in situ mining" (Probst et al. 2016). In the former, asteroids, in entirety or in part, are captured and transported to a designated location for subsequent resource extraction. In the latter, asteroid resources are concentrated or extracted in the unaltered orbit of the asteroid prior to transport. In situ mining allows for more efficient transport at the cost of increased reliance on autonomy; the communication delay between Earth and NEAs is often several minutes each way. Asteroid capture would enable near real-time manoeuvres and shorter delays between extraction and sale, allowing operations to respond to changes in demand. This comes at the cost of decreased transportation efficiency and increased propulsion needs.

Depending on the target resource, the degree of autonomy required to run a mining operation, including troubleshooting and mitigating unexpected events, is beyond the capabilities of current technology, leading some researchers to suggest asteroid capture is the only viable option (e.g. Mazanek et al. 2015). While technologically feasible at small scales, asteroid capture's efficiency is severely limited by the maximum possible mass retrieved. It is important to note that the complexity of resource extraction depends on the target resource and asteroid. Extraction of volatiles, like water, from rocky or rubbly asteroids is presumably a simpler task than the extraction of precious metals from a monolithic asteroid of solid FeNi alloy. The former may even be within the capabilities of current autonomous robotics (Trans Astronautica Corporation: http://www.transastracorp.com). The estimates below will account for transportation only and not the engineering cost of harvesting and/or concentration the target resource.

A study by Brophy et al. (2012) investigated the feasibility of capturing a boulder from a large NEA, or an entire small NEA, and bringing it to cis-lunar space. They found that current propulsion technology can transport a 7 m diameter asteroid of ~ 500 t from a favourable orbit to cis-lunar space in ~ 10 years. The study estimated the cost of such a venture to be ~ \$2.6B. This estimate was based on the orbit of asteroid 2008 HU4, the eighth most accessible of all known NEAs with a ΔV of 3.91 km s^{-1} (Benner 2018). Operations at asteroids with ΔV's of up to 4.5 km s^{-1} will be more expensive. It should also be noted that the Brophy et al. (2012) study includes a 30% (\$611B) buffer for reserves.

Transporting 500 t of material from a NEA in a favourable orbit to cis-lunar space for \$2.6B is equivalent to \$5294 kg^{-1} (Brophy et al. 2012). This figure includes research, development, spacecraft testing, and the price of the launch vehicle. Removing all but the recurring costs from this estimate yields an expense of \$2634 kg^{-1} to transport asteroid material into cis-lunar space.

If the value of water in space is assumed to be \$5000 kg^{-1}, a 90% pure concentrate is worth \$4500 kg^{-1} and unprocessed asteroid material at 16 wt.% is worth \$800 kg^{-1}. With the same 90% extraction rate, the material's value is \$720 kg^{-1}. Accounting for the cost of transport, the concentrate provides net gains of \$1866 kg^{-1} and the non-concentrated material incurs losses of \$1914 kg^{-1}. The case for in situ concentration is, therefore, strong, unless advances in propulsion technology can reduce transport costs by a factor of ~ 4. It is important to note that the value of water in space is estimated to be half of \$10,000 kg^{-1}, the canonical cost of launching mass from Earth's surface to LEO. The validity of this figure could soon change due to recent innovations in the commercial space launch sector. For example, SpaceX's Falcon 9 can bring payloads to LEO for \$2719 kg^{-1} and their Falcon Heavy is purported to do the same for \$1411 kg^{-1}, although the latter has only a single test flight to date (http://www.spacex.com/about/capabilities). The rockets are advertised to deliver mass to geosynchronous transfer orbit (GTO) for \$7470 kg^{-1} and \$3371 kg^{-1} respectively. If SpaceX's Falcon Heavy matures into a reliable technology, it represents a significant decrease in the value of resources in space. Similar degrees of innovation will have to be made in the production of asteroid resources to ensure a competitive advantage.

Extraction

In this, the final phase, resources are (further) concentrated and processed into final products. The following methods are conceptual in nature but draw on proven technology when possible.

Water can be extracted from asteroids by thermal dehydration of phyllosilicate minerals (e.g. King et al. 2015). Trans Astronautica Corporation (TransAstra) is a Los Angeles based company developing its own method of thermal dehydration called optical mining (https://www.nasa.gov/directorates/spacetech/niac/2017_Phase_I_Phase_II/Sustainable_Human_Exploration/). Its concept is to use concentrated sunlight and a containment bag to simultaneously extract volatiles and excavate the asteroid. In a full-scale test using a synthetic CI-like asteroid and a 10 m diameter solar collector they successfully demonstrated their technology. As predicted, the escaping volatiles caused the host rock to fracture, continually exposing fresh surfaces. Once liberated, the volatiles can be separated and purified by fractional distillation.

Most NEAs are understood to be "rubble-piles" or unconsolidated rock fragments held together by electrostatic, Van der Waal, and gravitational forces (Daniels 2013; Mazanek et al. 2015). A popular suggestion is to concentrate metallic phases by combing their surfaces with an electromagnetic rake (Kargel 1994).

Biomining techniques use microbes to extract metal from ores. Globally, ~ 20% of copper and ~ 5% of gold are extracted via biomining (Johnson et al. 2013). A paper by Klas et al. (2015) explores the feasibility of utilizing biomining on asteroids. The authors suggest extremophiles – microorganisms resistant to extremes in temperature, pressure, pH and radiation – may be of potential use for space-biomining applications. All are dependent on the presence of liquid water, however, so construction of an enclosed volume in which an appropriate temperature and atmosphere can be maintained is required. In addition to metal extraction, some microbes are also capable of methanogenesis (Klas et al. 2015). These microorganisms consume compounds like acetate, hydrogen, and carbon dioxide, materials found in carbonaceous asteroids, and produce methane. This simple hydrocarbon is a viable alternative to liquid hydrogen for rocket propellant as it is nearly as efficient, less hazardous, and allows for denser and warmer storage. Klas et al. (2015) suggest that the high surface area to volume ratio of rubble-pile asteroids is advantageous for biomining, because of both increased exposure and the unconsolidated nature that provides natural radiation shielding for deeply penetrating microbes.

While originally demonstrated on nickel oxides, the Mond process can also be used to purify metals from alloys. First described in 1890, the process uses carbon monoxide to form nickel carbonyl ($NiCO_4$) which is then decomposed to form pure nickel, impure residue, and carbon monoxide (Mond et al. 1890). The resultant nickel can be deposited onto a substrate or as a powder. Other metals like iron and chromium also form carbonyls and can be similarly extracted. Iron and nickel can be used for structural fabrication and 3-D printing (from their powders) while the residues will be PGE-enriched.

When considering the logistics of space-based resource production it is also prudent to consider the environmental impact. On the one hand, moving a portion of resource production into space reduces the quantity of waste and pollutants that must be accommodated by the Earth (Hlimi 2014). Further, if production is fully automated then the risk to human health associated with the use of chemicals like nickel carbonyl can be negated. In the long-term, minerals important to renewable energy production could be sourced from NEAs, reducing the cost of renewable energy technologies (Metzger 2016). At some point it may even be possible to generate solar power in space for use on Earth while adding zero carbon to our atmosphere (Metzger 2016).

On the other hand, there are legal and ethical concerns regarding the contamination of asteroid material. Pristine asteroid material has high scientific value (e.g. NASA 2018b); processing large quantities of asteroid material for economical benefit could potentially destroy clues regarding the nature and evolution of our solar system that lay previously unspoiled for more than four billion years. The legal implications of contaminating extraterrestrial material is discussed below. A resource production scheme that removes a substantial portion of an asteroid's mass also has the potential to alter its orbit, necessitating great care as to not inadvertently send an asteroid on a collision course with Earth. There is also concern that any form of increased activity in space will contribute to the growing problem of space debris, fragments of anthropogenic material, particularly those that orbit the Earth that can cause destructive impacts with satellites and spacecraft (Hlimi 2014). As with resource production on Earth, asteroid mining missions must predict and minimize any deleterious effects on the surrounding environment.

ASTEROID MINING AND THE LAW

In addition to the logistical challenges of asteroid mining, one must also consider the legal implications. Early space legislation was drafted at a time when space was the exclusive domain of governmental bodies and so little thought was given to the potential commercialization of space and asteroid mining.

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More recently, some governments have made efforts to encourage private sector involvement in space resources, but complications persist.

International Space Law

The history of space policy begins with the creation of the Committee on the Peaceful Uses of Outer Space (COPUOS) by the United Nations General Assembly in 1958. Made permanent the next year, the Committee was formed to "*govern the exploration and use of space for the benefit of all humanity: for peace, security and development*" (COPUOS 2017a). Originally consisting of 18 members, COPUOS now has 84, including all major spacefaring nations. COPUOS was pivotal to the creation of the five treaties and the five principles that govern the exploration of outer space (COPUOS 2017a). The first and most influential of the treaties is the "Outer Space Treaty" of 1967. Of the remaining treaties and principles, the "Moon Agreement" of 1984 is most pertinent to SRU.

The Outer Space Treaty

The Outer Space Treaty (OST) is the most fundamental piece of space legislation produced to date. Officially named the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, the treaty entered into force on October 10, 1967 after it was ratified by the three depository governments of the United States, the Soviet Union, and the United Kingdom (COPUOS 2017b). The Treaty contains 27 articles. The first 12 directly govern the exploration and use of space while the last 15 are administrative. Of the 12 that deal with space directly, I, II, VI, IX, and XII have potential ramifications on SRU including asteroid mining.

Article I sets the tone for the document by stating that the "*exploration and use of outer space […] shall be carried out for the benefit and in the interests of all countries […] and shall be the province of all mankind*" (United Nations Resolution 2222 (XXI) 1966). This passage illustrates the overarching intent of the Treaty; that outer space should be made, and remain, available to all parties equally.

Article II states that "*outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means*" (United Nations Resolution 2222 (XXI) 1966). The word 'national' would suggest that appropriation of celestial bodies is only forbidden for governments; however, as noted in Article VI, States are responsible for all national activities in space, be they governmental or not. This article forms the basis of the argument against the legality of the acquisition and sale of space resources.

Article VI places international responsibility on States for national activities in space, be they governmental or non-governmental. States must authorize and continually supervise the activities of non-governmental entities in their jurisdiction (United Nations Resolution 2222 (XXI) 1966).

Article IX forbids cross-contamination of Earth and celestial bodies. While the introduction of processed asteroid materials to Earth are unlikely to cause the "adverse changes in the environment" that the article prohibits, certain extraction techniques (e.g. biomining) could be deemed to contaminate the asteroid and, therefore, be impermissible according to this Article (United Nations Resolution 2222 (XXI) 1966).

Article XII states that stations, installations, vehicles, and equipment in space are to be made available on a reciprocal basis for visits from representatives of other States Parties to the Treaty (United Nations Resolution 2222 (XXI) 1966). A possible implication to the space mining industry is the inability to preserve the exclusive knowledge of novel technologies and methods.

The Moon Agreement

The *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* (Moon Agreement) entered into force on July 11, 1984 (COPUOS 2017b). The Moon Agreement directly addresses the exploitation of space resources, a unique feature among the five UN space treaties. It should be noted that for the purposes of this Agreement the term Moon refers to not only the Moon but also any celestial body within the solar system.

Article 6, paragraph 2 of the Agreement asserts that States Parties may collect and distribute samples of the Moon for scientific study (United Nations 1979). States Parties may also use appropriate quantities of space resources in support of their missions (ISRU).

Article 11, paragraph 3, reaffirms the prohibition of sovereign claims laid out in Article II of the OST by stating that "*neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person*" (United Nations 1979). Paragraph 5 goes on to say that States Parties to the Agreement agree to form "*an international regime […] to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible"* (United Nations 1979). Paragraph 7(d) establishes "[a]*n equitable sharing by all States Parties in the benefits derived from those resources" with special consideration for those directly or indirectly involved and to developing nations*" (United Nations 1979).

The Moon Agreement thus prohibits the commercialization of space resources except by an international regime designed for the mutual benefit of all States Parties. Fortunately for private asteroid mining firms, the Agreement has only 17 members, none of which are major players in space exploration.

National Legislation

To date, two nations – the United States and Luxembourg – have passed legislation encouraging private sector involvement in space resource development by explicitly granting their citizens the legal right to own and sell space resources.

The United States

The United States Commercial Space Launch Competitiveness Act (CSLCA) came into force on November 25, 2015 (United States Commercial Space Launch Competitiveness Act of 2015). Title IV section 51303 states that it is legal for U.S. citizens to engage in the commercial exploration and recovery of space resources. U.S. citizens are granted the right to "*possess, own, transport, use, and sell*" any obtained space resource in accordance with applicable law, including U.S. international obligations. By its citizens exercising this right the bill claims that U.S. is not asserting sovereignty or claiming ownership of any celestial object.

Luxembourg

In July 2017 the small country of Luxembourg became the first European nation to pass space resource legislation with the *Loi du 20 juillet 2017 sur l'exploration et l'utilisation des ressources de l'espace* (Law of 20 July 2017 on the exploration and use of space resources) (Government of Luxembourg 2017). Effective August 1, 2017, the bill grants similar rights as the United States' CSLCA but with the modification that these rights are available not only to citizens, but also to any corporation with an office in the country of Luxembourg. US firms Planetary Resources and Deep Space Industries (acquired by Bradford Space) both have offices in the country.

There is a lack of consensus in the space law community as to whether these Acts are in accordance with the OST. Under international law, property rights can only be attributed by a superior power (Tronchetti 2015). This power, the State, can only attribute property rights if the State itself has rights to the property first. In this sense, for State governments to grant space resource property rights to their citizens they are in effect appropriating the property rights for themselves first. This is in violation of Article II of the OST. Others argue that the OST does not expressly prohibit the commercialization of space resources and national legislation such as these are valid interpretations of the rights afforded to each State in accordance with Article VI of the same treaty.

CURRENT STATE OF THE ASTEROID MINING INDUSTRY

Thus far, Planetary Resources has launched and tested two versions of their Arkyd spacecraft; Arkyd-3 Reflight in 2015 and Arkyd-6 in 2018 (Planetary Resources 2017). Their first spacecraft to collect data from asteroids, Arkyd-301, is in development. The Arkyd-301 will be designed to be small and inexpensive enough to permit the simultaneous deployment of multiple identical spacecraft by a single launch vehicle, each destined for its own target asteroid (Planetary Resources 2018). Spacecraft miniaturization, a trend also evidenced by the recent popularity of CubeSats, is the key to deploying enough spacecraft to explore numerous NEAs in a timely and cost-effective manner. The Arkyd-301 will perform compositional surface mapping and will also include four on-board probes to directly sample the asteroid (Planetary Resources 2018). Data from the Arkyd-301 fleet will be used to select Planetary Resources' first mining target and inform the development of their mining architecture. Planetary Resources missed funding goals throughout 2018 and has been forced to downsize. On October 31, 2018, they were purchased by the blockchain company Consensus Systems Inccorporated (ConsesSys Inc.), leaving their future somewhat uncertain.

Until their purchase by Bradford Space in January 2019, Deep Space Industries had placed an emphasis on developing propulsion technology, with two propulsion systems, Comet and Meteor, being available for purchase. Bradford Space have continued development of the Comet thruster (Bradford Space 2019a). They have also continued the development of the low-mass, low-cost prospecting Xplorer spacecraft, now renamed Explorer. This spacecraft will be capable of transporting a 10 kg payload from low Earth orbit to interplanetary space (Bradford Space 2019b).

Planetary Resources, Bradford Space, and TransAstra are not the only companies working towards making asteroid mining a reality. Luxembourg based Kleos Space S.à.rl., a subsidiary of UK based Magna Parva Limited, is collaborating with the Luxembourg Institute of Science and Technology and has received funds from the Luxembourg Government to develop in-space manufacturing technology (LIST 2017). Aten Engineering (https://www.atenengineering.com), headquartered out of Portland, Oregon, is working towards making efficiencies in the domain of asteroid detection and characterization. OffWorld (https://www.offworld.ai) is a robotics company with branches in Pasadena, California and Luxembourg. Their long-term goals are to create autonomous industrial robots for use on Earth, the Moon, Mars, and asteroids.

PRIVATE-PUBLIC PARTNERSHIPS

Private–public partnerships (PPPs) are designed to split the cost, risk, and effort between government and industry. The private partner accepts more risk and responsibility versus a traditional arrangement, incentivizing increased efficiency. The Commercial Orbital Transportation Services (COTS) and Commercial Resupply Services (CRS) programs, initiated by NASA's Commercial Crew and Cargo Program Office in 2006 and 2008, culminated in the development and deployment of SpaceX's Dragon and Orbital Sciences Corporation's (now Orbital ATK) Cygnus, the first two private spacecraft to dock with and resupply the International Space Station (Hackler 2014).

The success of COTS has been described as a "new era in spaceflight" (Hackler 2014). A paper by Entrena Utrilla (2017) proposes the simultaneous and synergistic development of an asteroid resource utilization PPP dubbed Asteroid COTS. Given the recent success of PPPs enjoyed by NASA, and the potential gains the agency would see from advancement of commercial spacecraft and the installation of cis-lunar propellant depots, an asteroid resource PPP seems a likely possibility. NASA has awarded contracts to asteroid mining companies before; Deep Space Industries and Planetary Resources each received two contracts as part of the Asteroid Redirect Mission (Mahoney 2014).

OPPORTUNITIES FOR CANADA

Canada has a long and proud mining tradition (e.g. Cranstone 2002). This pillar of the economy is underpinned by mineral exploration and prospecting and there are more than 2000 Canadian mining and mineral exploration companies. These companies operate worldwide and account for nearly 37% of the budgeted global exploration expenditures. In 2016, Canada produced $111B worth of minerals (including mineral fuels), the sixth most of any nation (Reichl et al. 2018). Mining is Canada's third largest industry, worth 8.5% of its GDP in 2018 (Statistics Canada 2018). At the same time, Canada also has a distinguished and celebrated history of space robotics, most famously the Canadarm and Canadarm2, both built by MacDonald, Dettwiler and Associates (MDA), now part of Maxar Technologies Ltd. Canadian space companies are also well known for their expertise in the instrumentation needed for prospecting NEAs, for example, the OSIRIS-REx Laser Altimeter (OLA) instrument on the OSIRIS-REx spacecraft that is currently mapping asteroid Bennu (Daly et al. 2017).

It is also important to note that investment in technologies required for asteroid mining also stands to benefit mining on Earth through the development of spin off technologies. Indeed, interest in technology developments to aid mineral exploration and mining is growing. In an article in the Globe and Mail (March 30, 2014) entitled "*Innovation key to maintaining Canada's leader status*", Lee Hodgkinson wrote "*All Canadian resource industries will need to adopt an innovative approach through extensive research and development, use of technology, and promote an influx of new young talent.*" In a 2012 report entitled *100 Innovations in the Mining Industry*, the Ontario Mining Association noted several innovations in exploration, including lidar, portable spectrometers, and remote predictive mapping, all key strengths of the Canadian space community.

Considering the above, asteroid mining might seem like a natural fit for Canada; however, despite having the necessary expertise, the Canadian private sector is so far devoid of any companies working directly on asteroid mining. In addition, the government has not passed any space mining legislation and there is little indication on where they stand on the legality of SRU. However, a major step forward was the release of the Canada Mineral and Metals Plan (CMMP) in March 2019, which highlights SRU as a new frontier in mining for Canada; this plan also calls for the development of a policy approach for SRU in Canada (NRCan 2019). Only a few days before the release of the CMMP, the Prime Minister of Canada also announced that Canada is joining NASA on the Lunar Gateway initiative that will see humans return to the Moon. In summary, there is a significant opportunity for Canada to invest in SRU – for the Moon and Mars, as well as asteroids – given the current state of the mining and space exploration sectors in Canada.

THE FUTURE

Economic utilization of asteroid resources is not an impossible goal, but before the wealth of the solar system can be realized there are significant hurdles to overcome. Advances in spacecraft propulsion technology and robotic resource extraction autonomy will be required to process material at a sufficient scale to be economical. Before this stage, however, the catalogue of NEAs, with an emphasis on more accurate spectral data, must be expanded. The paucity of prospective asteroid mining targets (1 in 2300 for water) dictates that extensive ground-based observations must be made prior to the selection of asteroids to which prospecting spacecraft will be sent. New NEA discoveries should have their spectra immediately characterized by follow up observations and efforts should be made to make spectral observations for as many known NEAs as possible. Since asteroid resources are likely to be acquired via appropriation of the resource only, and not of the host asteroid, the exclusive knowledge of prospective asteroids is extremely valuable, even before spacecraft visitation or the commencement of a mining operation.

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