

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

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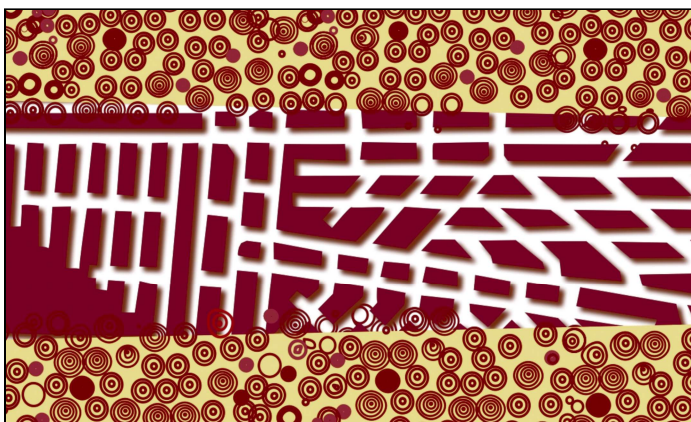
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Résumé de l'article

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 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 nordouest 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.

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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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 – $(\text{Fe}_{2+}, \text{Mg})_5\text{Al}(\text{AlSi}_3\text{O}_{10})(\text{OH})_8$) 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 19th 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.

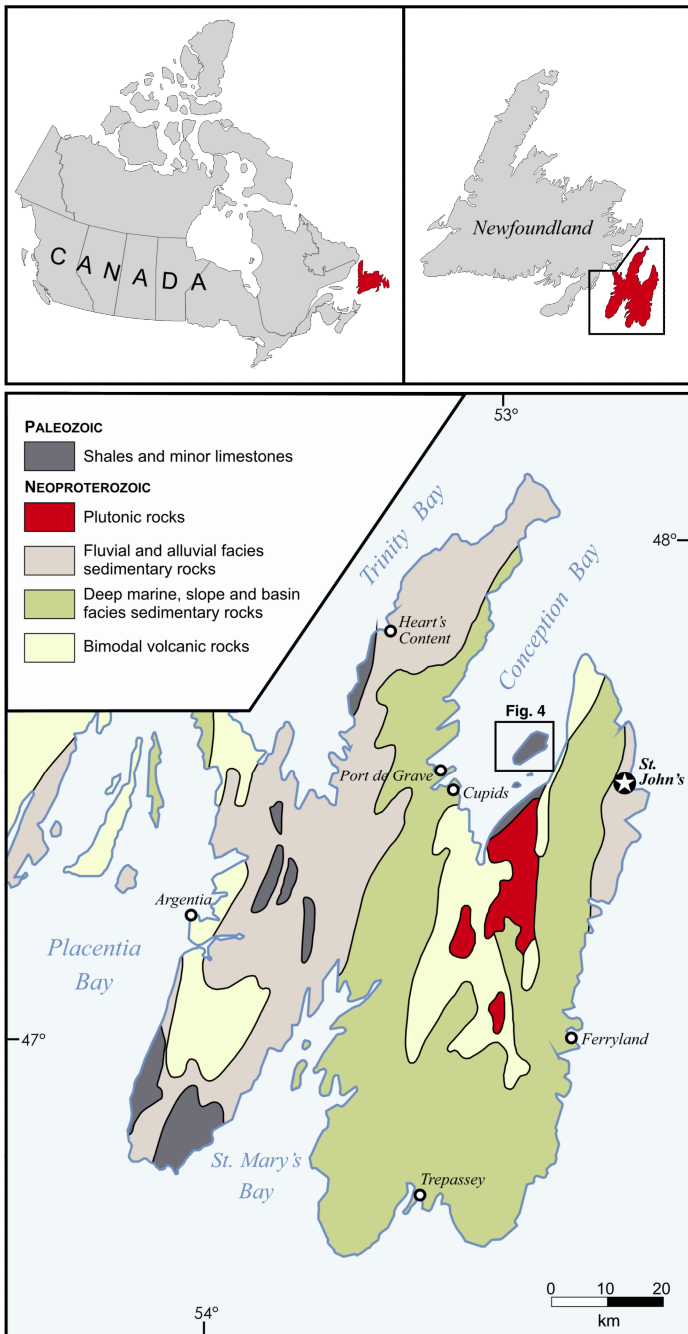


Figure 1. Location maps and geology of the Avalon Peninsula, eastern Newfoundland. Source from the Geological Survey of Newfoundland and Labrador.

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 Iron 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*

red sandstone about eight feet thick” as cropping out on the north-west 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

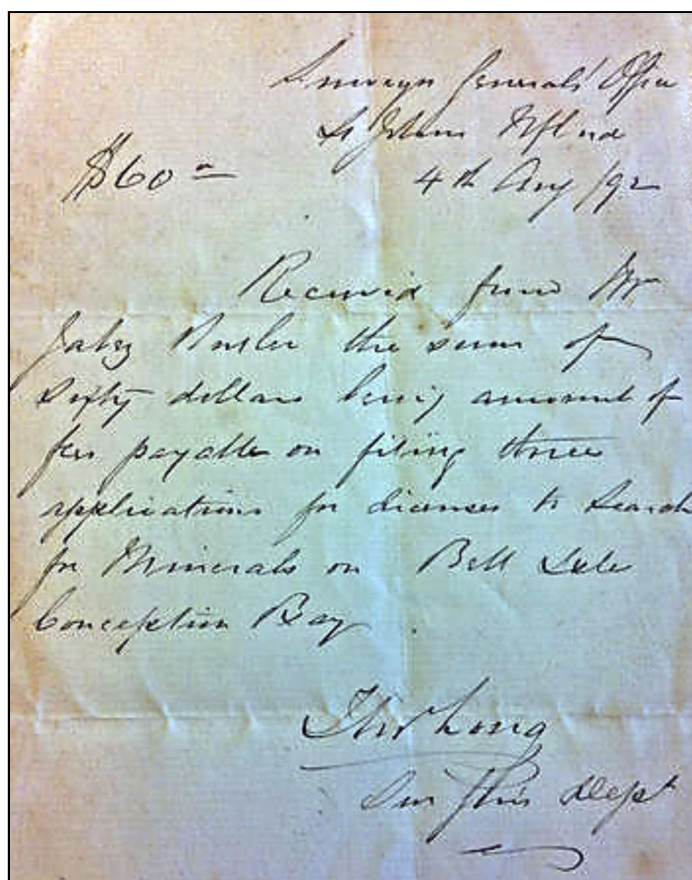


Figure 2. Receipt in the amount of \$60 filed by Mr. Jabez Butler on 4 August 1892 for “...fees payable on filing three applications for licenses to search for Minerals on Bell Isle Conception Bay.” Courtesy of The Rooms Provincial Archives, Newfoundland and Labrador.

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

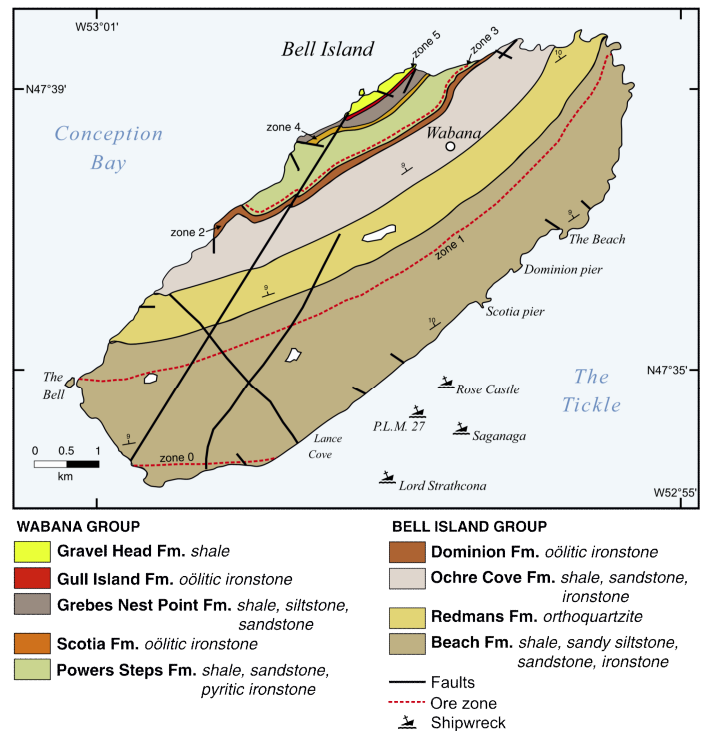


Figure 4. Geology of Bell Island, Conception Bay, Newfoundland (modified from Todd et al. 2019).

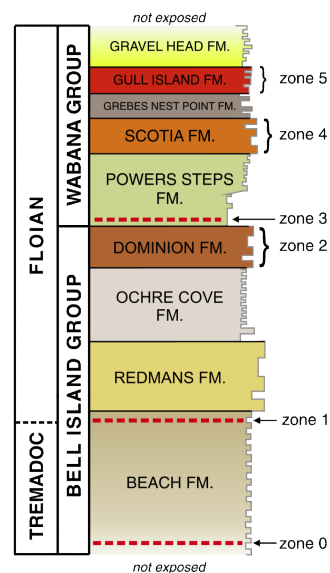


Figure 5. Simplified stratigraphy of the Bell Island and Wabana groups and ore zones (modified from Ranger et al. 1984).

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 oölitic consist of hematite and chamosite. The bed varies in thickness from 2 to 3 m with an average mined thick-

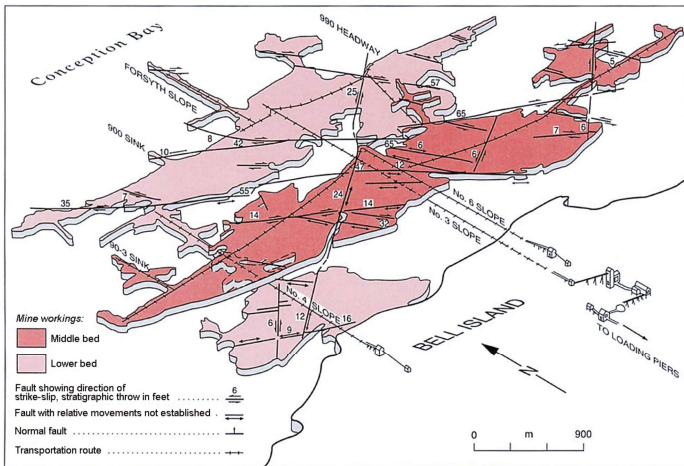


Figure 6. Schematic map of submarine mine workings showing ore trend and extent beneath Conception Bay (Lyons 1957).

ness of 2.5 m (Ranger 1979). A 10–15 cm thick distinctive grey bed of chamosite oörites 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 geo-

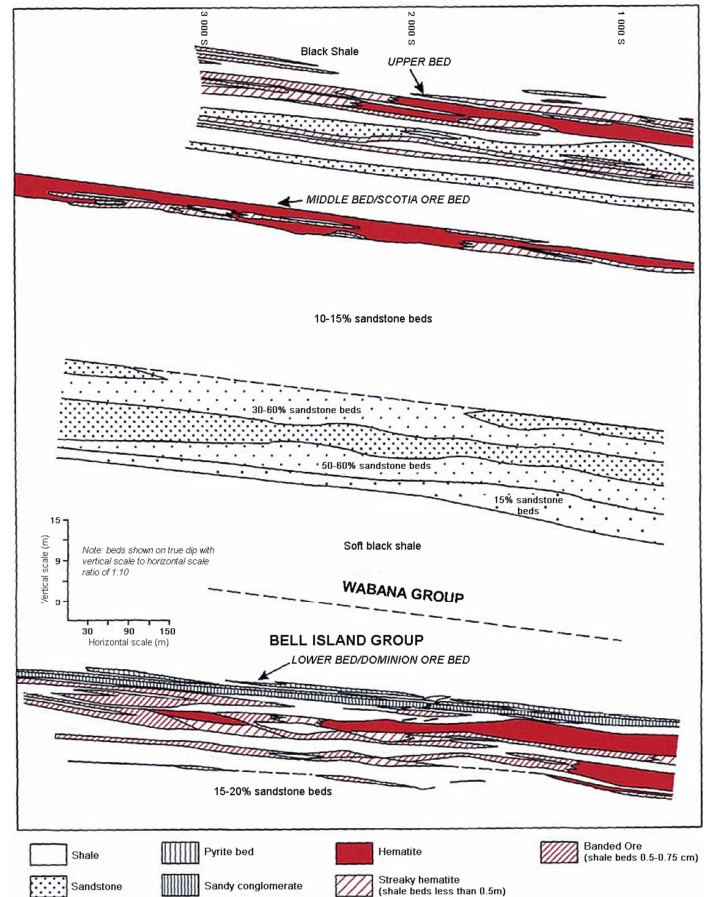


Figure 7. Cross section through the Upper, Middle, and Lower beds of the Dominion, Scotia, and Gull Island formations (Lyons 1957).

logical 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.

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 oörites 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 nuclei to oörites or in interstices between oörites (Hayes 1915). The outer layers of the oörites 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 oörites 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 oörites 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

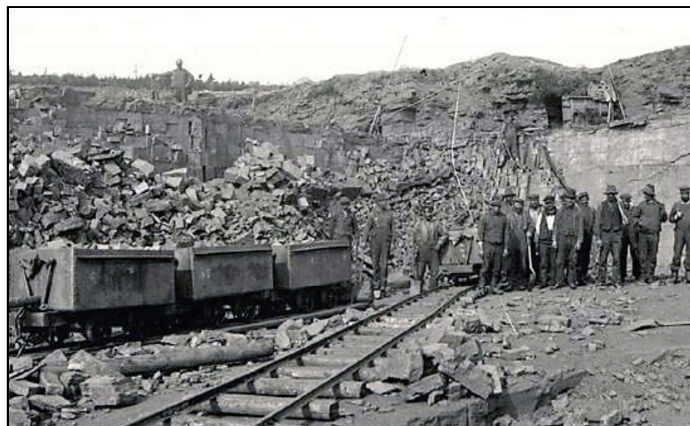


Figure 8. Surface mining at No. 1 mine, Scotia Company ca. 1902. Source: Memorial University of Newfoundland–Digital Archives Initiative.

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.”

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 cobbled) to upgrade it; the ore broke into rhombohedral fragments, ca. 20 cm in length, along a conjugate joint-set when struck by a pickaxe. These fragments were cobbled 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



simple title, by exercising their \$120,000 purchase option with the Butlers on 4 March 1899—originally negotiated by Chambers five years 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 km² 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 km².

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 subhorizontal 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

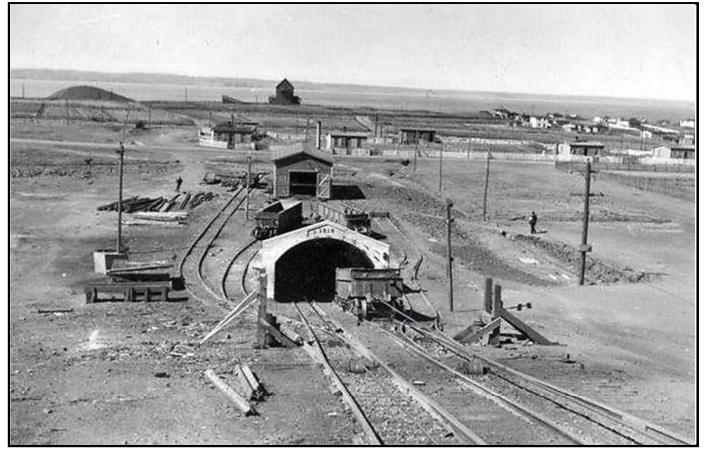


Figure 9. The adit of Scotia Company's No. 3 double slope submarine mine and No. 6 mine deck head in the distance. Source: Memorial University of Newfoundland–Digital Archives Initiative.

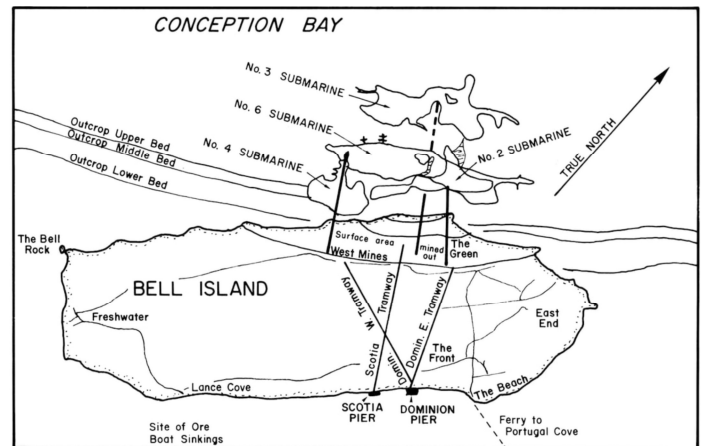


Figure 10. Map of Bell Island showing location of the submarine mines, slopes, and surface infrastructure (Anson 1951).

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

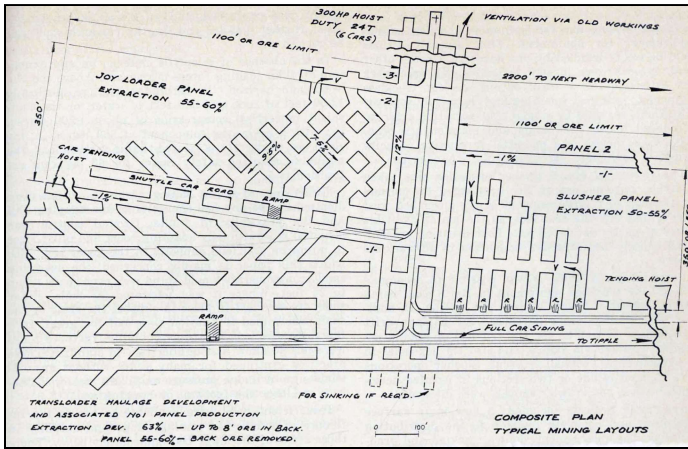


Figure 11. Composite plan of mining layout for No. 3 mine (Southey 1969).



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).

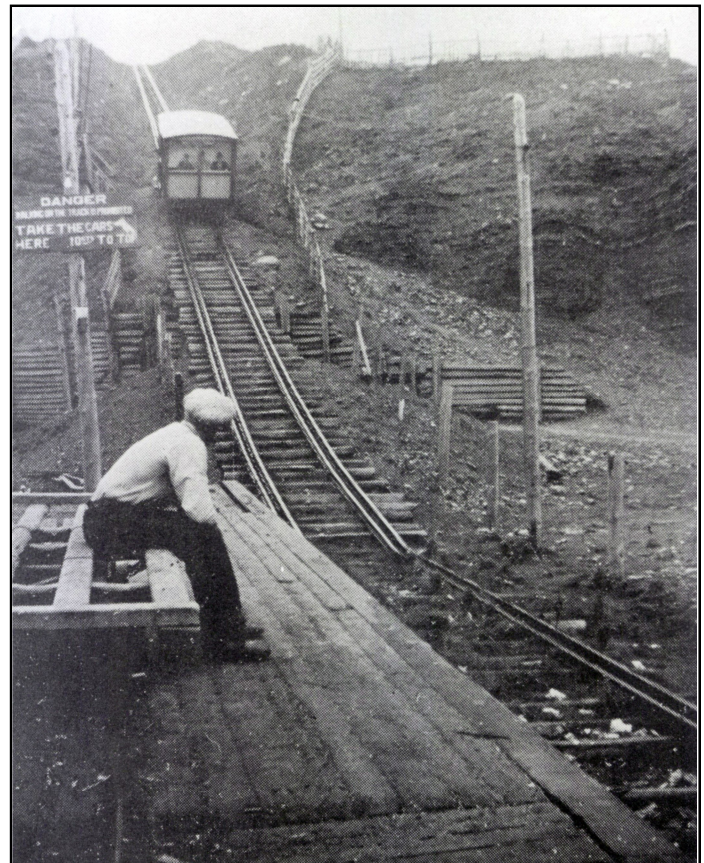


Figure 14. Cable drawn, 0.6 m (2 foot) narrow gauge tramway used to transport ore from the mine to the piers and miners from the piers to the mine adit. Source: Memorial University of Newfoundland–Digital Archives Initiative.

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 led 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



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

to the Dominion Steel and Coal Company Limited (DOSCO) of Nova Scotia, a holding company formed by former BESCO investors.

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 Rugeberg (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 tippie 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. Conveyor 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 ($\text{Ca}_4(\text{PO}_4)_2\text{O}$), 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 km² (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 km² 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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