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A CLASSIFICATION OF IRON FORMATIONS BASED ON DEPOSITIONAL ENVIRONMENTS

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ABSTRACT

Two groups of ferruginous sediments are recognized: (1) chemically precipitated iron-formations composed mainly of thinly banded chert and iron minerals; (2) ironstones commonly consisting of oolitic chamosite–siderite–goethite beds with appreciable clay and detrital constituents. Both groups form under a wide range of depositional environments and have distinctive lithological and mineralogical facies. Two principal types of siliceous iron-formation are recognized, Lake Superior and Algoma, based on the characteristics of their depositional basins and the kinds of associated rock. The Lake Superior type was deposited with quartzite, dolomite and black shale in continental-shelf environments, and the Algoma type with volcanic and greywacke rock assemblages along volcanic arcs, rift zones and deep-seated fault and fracture systems. Factors pertinent to the classification of depositional environments for chemical precipitation of iron and silica in iron formations include neritic, continental-shelf and deep-ocean basin environments; proximity to volcanic centres, rift zones, fault systems; type of associated sedimentary and volcanic rock; mineralogy, sedimentary features and lithological facies of the iron formation.

Keywords: iron formation, ironstone, Lake Superior type, Algoma type, depositional environment, oceanic ridge, volcanic arc, continental shelf.

SOMMAIRE

On distingue deux groupes de sédiments ferrugineux: (1) précipités chimiques, contenant surtout des cherts finement laminés et des minéraux de fer; (2) sédiments enrichis en argile et en éléments détritiques, caractérisés par des lits oolithiques à chamosite, sidérite et goethite. Les deux groupes résultent d'environnements de dépôt très variés et montrent plusieurs facies lithologiques et minéralogiques. De plus, on distingue deux types principaux parmi les formations de fer siliceuses, selon le caractère du bassin sédimentaire et des roches associées. Les exemples du type "Lac Supérieur", interstratifiés avec quartzite, dolomie et shale noir, proviennent de la plate-forme continentale; ceux du type "Algoma" sont associés aux roches volcaniques et aux grauwackes le long d'arcs volcaniques, zones de rift, et réseaux de failles et de cassures profondes. La classification des milieux de dépôt des précipités chimiques de minéraux de fer et de silice repose sur les critères suivants: environnement du bassin (milieu néritique, plate-forme continentale ou fond océanique); proximité d'un centre volcanique, d'une zone d'extension ou d'un système de failles; association de lithologies sédimentaire et volcanique distinctes; minéralogie, structures sédimentaires et facies lithologique de la formation de fer.

(Traduit par la Rédaction)

Mots-clés: formation de fer, sédiment ferrugineux argileux, type du lac Supérieur, type Algoma, milieu de dépôt, crête océanique, arc volcanique, marge continentale.

INTRODUCTION

Ferruginous sedimentary rocks were classified in two major categories, ironstones and iron formations, in Volume I of the Geological Survey of Canada's *Economic Geology Series* on the iron deposits of Canada (Gross 1965). During the preparation of this volume in 1959 it was recognized that the siliceous iron-formations occur as two major types and can be classified on the basis of associated types of rock, lithological features and interpretation of their depositional environment (Fig. 1). Since the introduction of this classification, more detailed work on the petrography, stratigraphy, sedimentation, tectonic setting and depositional environment of iron formations and associated rocks has demonstrated an even wider contrast in conditions of occurrence of iron formation (Gross 1973). An attempt is made in this paper to outline the relationships among different sedimentary environments as conceived in a general tectonic framework and to update the basis for the classification of iron formations.

DEPOSITIONAL ENVIRONMENTS

The well-known Lake-Superior-type iron formations, widely distributed in Proterozoic rocks, were deposited in near-shore continental-shelf environments and are associated with dolomite,

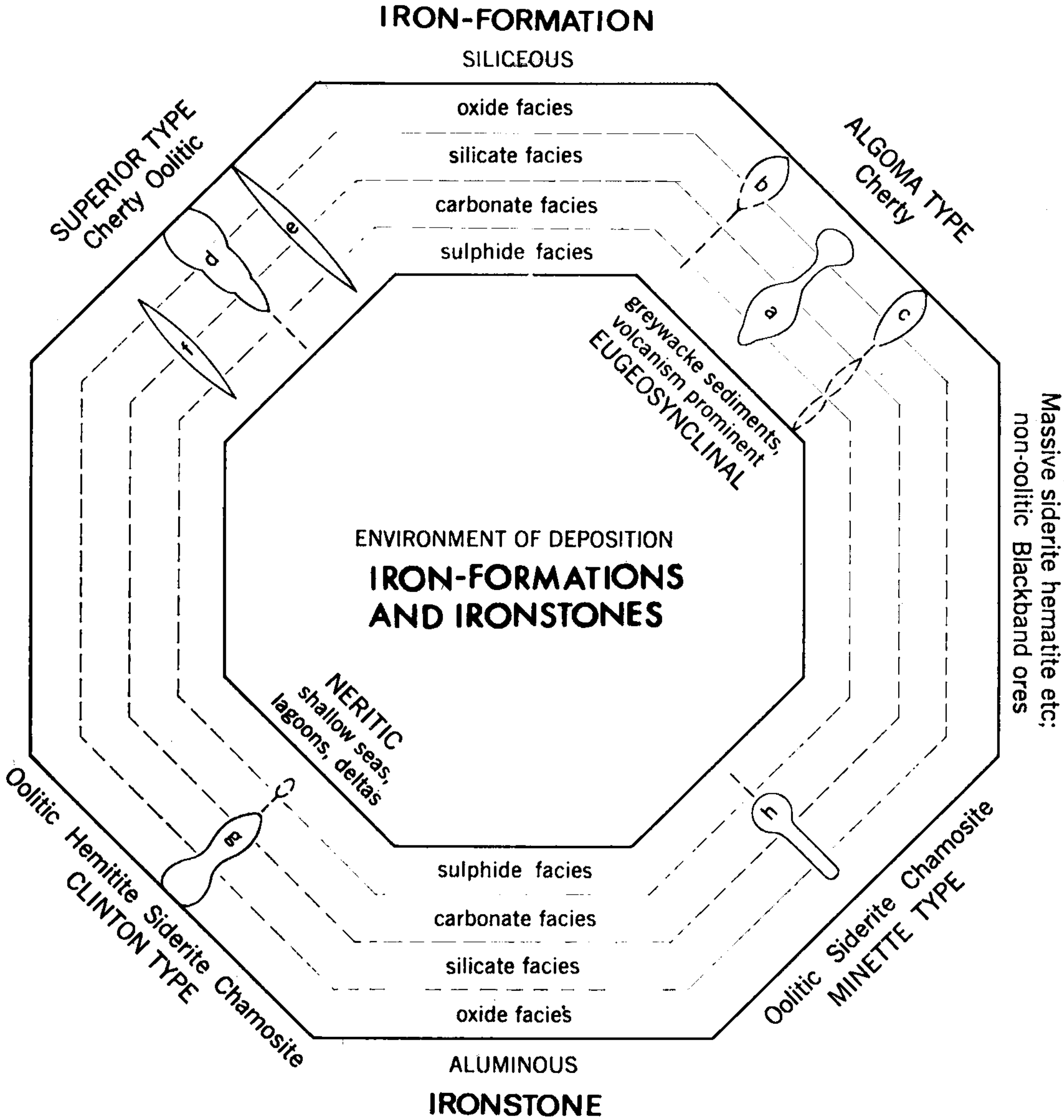


FIG. 1. Diagram showing major types of chemically precipitated iron formation and ironstone with their sedimentary facies and depositional environment. Examples are from (a) Michipicoten, Ontario, (b) Moose Mountain, Ontario, (c) Temagami, Ontario, (d) Knob Lake, Labrador and Québec, (e) Iron River, Michigan, (f) Gunflint and Biwabik iron formations, Ontario and Minnesota, (g) Wabana, Newfoundland, (h) Clear Hills, Alberta (after Gross 1965).

quartzite, black shale and minor amounts of tuffaceous and other volcanic rocks (Gross 1965). The Algoma-type iron formations, found in all ages of rock, are consistently associated with greywacke sedimentary units and volcanic rocks; they apparently formed close to volcanic centres and were produced by fumarolic, effusive and exhalative hydrothermal processes related to volcanic centres (Gross 1965). Oxide, silicate and carbonate lithological facies are common to both these groups, and polymetallic sulfide facies, bearing copper, zinc, lead, silver, gold, iron and manganese, are commonly associated with the other Algoma-type facies near

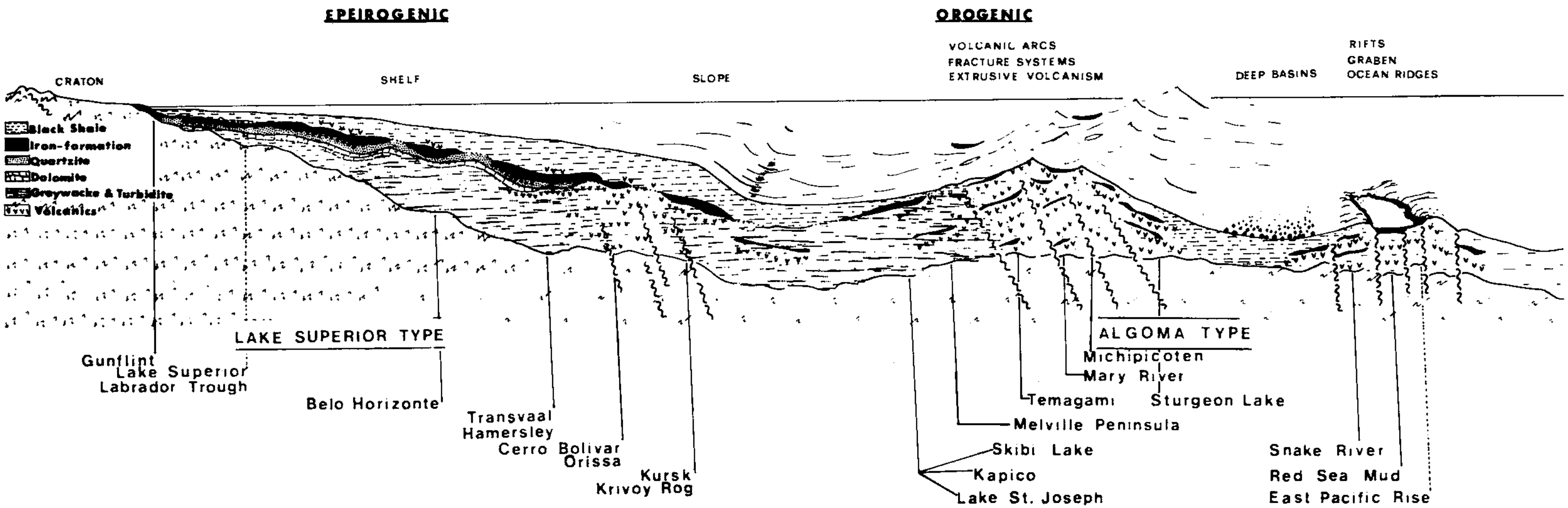


FIG. 2. Tectonic environments of deposition of iron formation.

centres of volcanism (Gross 1965, 1967, James 1954, Stanton 1960, Moorhouse 1965, Goodwin 1961, 1965).

Banded siliceous ferruginous sedimentary units most commonly occur in Lake-Superior- and Algoma-type depositional environments. Extensive iron-formation deposition also took place in marine rift basins, along fault scarps, in grabens and along contemporary ocean ridges (Gross 1973, Piper *et al.* 1975, Bischoff 1969). Iron formations recognized as of classical Lake Superior type were formed on continental shelves, relatively near the shore (James 1954, Gross 1965). It is now realized that many other examples of iron formation classified at one time as Lake Superior type have associated sedimentary rocks and features indicative of deposition in deeper water far offshore on the continental shelf or on slopes adjacent to or in deep marine basins (Alexandrov 1973, Plaksenko *et al.* 1973). On the other hand, Algoma-type iron-formation deposition extends from the multifacies development found near volcanic centres to the predominant oxide facies extending far into the greywacke and turbidite sediments. These sediments were deposited at considerable distances from the volcanic centres and the sources of the hydrothermal effusions that provided the iron, silicon, manganese and other elements present in these rocks (Gross 1970, 1973, Goodwin 1973, Alexandrov 1973).

Figure 2 shows important examples of different types of iron formation and the order in which they occur (1) in relation to near-shore and deeper water shelf conditions and (2) with respect to their proximity to volcanic centres or to rift and graben tectonic systems. The Lake Superior and Labrador Trough formations have associated dolomite and quartzite, indicating mature sediment development on a marine continental shelf, whereas the Krivoy Rog iron formations have a high proportion of volcanic rocks, turbidite sediment and deeper water features (Gross 1968, Plaksenko *et al.* 1973, Alexandrov 1973, Zajac 1974). The depositional environment of the Hamersley iron formation in Australia is not considered to be an anomalous type under this classification scheme, although it has distinctive sedimentary features indicative of deposition under stable tectonic conditions in the basin. These conditions led to the formation of sequences of microbanding that can be correlated over a distance of two hundred kilometres (Trendall 1973).

Examples of Algoma-type iron formation are shown in relative order from those near volcanic centres to others such as Lake St. Joseph and Skibi Lake in Ontario, deposited some distance from effusive volcanic centres. Except for their smaller size, they compare directly with Kursk and Krivoy Rog iron formations listed with the Lake-Superior-type sequences. Some of the iron formations in deep water and turbiditic sedimentary rocks may have formed by deposition of iron-bearing minerals and silica derived from ocean-ridge systems rather than from volcanism associated with island-arc systems (Piper *et al.* 1975, Boström 1970).

Iron formations deposited in grabens and associated with rift systems range in age from the Cambrian–Precambrian Snake River beds in the Rapitan Group in the Yukon to the recent and contemporary sedimentation in the Red Sea grabens and along the East Pacific Rise (Gross 1973, James 1969, Piper *et al.* 1975).

Faults, rifts and graben systems along the margins of ancient cratons and continents have provided suitable environments for the deposition of iron formations, thick sequences of volcanic rocks and greywacke–turbidite sediments, as exemplified around the Ungava craton (Gross 1968, 1970, Dimroth *et al.* 1970) and in other parts of the Canadian Shield (Goodwin 1973). Iron formations deposited on the continental side of these marginal tectonic systems display typical features of Lake Superior type, and those on the seaward side of tectonic systems are more typical of Algoma type. Iron formations deposited within tectonic belts are usually more closely identified with the Algoma type. Depending on the relative position of the tectonic belt with respect to the continental margin, the iron formation present in grabens and fault-scarp basins near continental margins may have distinctive lithologies, as found in the Snake River iron formation (Eisbacher 1978). Those iron formations in basins at the outer edge of a continental shelf may resemble common Algoma-type lithologies, as shown in the Orissa and Krivoy Rog iron formations.

The very wide range of sedimentary environments in which precipitation of iron formation has taken place is indicated in Figure 2. To a greater or lesser extent, volcanic rocks are known to occur in, or in immediate association with, all the various environmental types of iron formation. There appears to be no age restriction for the occurrence and development of any of these types of iron formation, with the exception of the near-shore Lake Superior type, found only in Proterozoic rocks. The explanation for this exception is believed to relate to special worldwide tectonic features at that time and not to unique factors influencing sedimentation of silica and iron-bearing minerals, such as atmospheric changes or biogenic developments (Cloud 1973, LaBerge 1973).

Classification of the iron formations is based on descriptive data for the various lithofacies of iron-rich sediment present, their mineralogy, sedimentary features, associated rocks and their regional tectonic setting at the time of deposition and subsequent tectonic history. Table 1 indicates various kinds of data collected in the study and classification of an iron range. Synthesis and study of the descriptive data lead to interpretation of the various factors listed in the left margin of Table 2. The nature and character of the primary depositional basin and the physical and chemical environment for deposition and precipitation of the iron-formation sediment are deduced from the study of these basin-environment factors.

Discussion

Numerous geological models have been outlined in the literature to account for significant factors that contributed to the formation and geological history of an iron-formation bed (Gross 1965, 1973, Goodwin 1962, 1973, James & Sims 1973, Semenenko 1973). It has become evident through the study of genetic models of the iron formations and iron-ore deposits that the banded siliceous iron-formation group of ferruginous sediments occurs in a wide variety of sedimentary-basin environments, ranging from stable epeirogenic to metastable orogenic tectonic conditions. The thickness and lateral extent of an iron formation depend directly on the tectonic stability of the sedimentary basin as well as on other sedimentary processes operating in the basin. The accumulation of siliceous iron-rich muds and ooze is controlled by the introduction or restriction of clastic sediment and by biochemical activity in the basin environment.

Fumarolic and hydrothermal emanations discharged near volcanic centres, along deep-seated fracture zones and from areas of high thermal gradient in the earth's crust are believed to be the principal sources of iron, silica and other metallic constituents in the iron formations

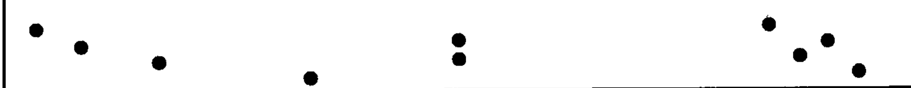
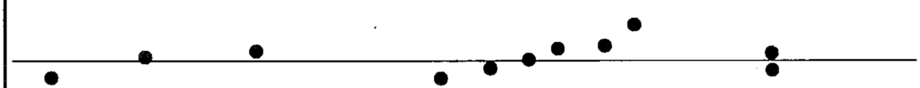
TABLE 1. ROCK DESCRIPTIONS IN THE CLASSIFICATION OF IRON-FORMATIONS

BASIN TYPES	LAKE SUPERIOR TYPE	ALGOMA TYPE	
TYPICAL BASINS	Lake Superior Gunflint Labrador Trough Belo Horizonte Transvaal Hamersley Cerro Bolivar Orissa Kursk Krivoy Rog	Michipicoten Mary River Temagami Sturgeon Lake Melville Peninsula Skibi Lake Kapico Lake St. Joseph	Snake River Red Sea Mud East Pacific Rise
TECTONIC ENVIRONMENT	EPEIROGENIC Cratonic shelf Slope	OROGENIC Volcanic arcs Extrusive volcanism, Fracture systems	Ocean ridges Rifts, Graben
ASSOCIATED ROCKS Sedimentary Volcanic acidic basic Intrusive	Black shale, Chert Quartzite, Dolomite Basic dykes, sills	← decreasing Chert Greywacke, Turbidites Tuffs Pyroclastics	Chert, Conglomerate Mudstones, Evaporites Volcanoclastics

IRON-FORMATION LITHOFACIES	Lake Superior type			Algoma type				
Oxide	X	X	X	X	X		X	
Silicate	x	x	x		x			
Carbonate	x					X		
Sulphide					x	x		X
Clastic								
carbon shale	x				x			
mud								
wacke				x	x	x		
sand								
Mixed facies	x		x	x	x	x	x	

MINERALOGY	
METAMORPHISM low high	
STRUCTURAL STYLE	

TABLE 2. A CLASSIFICATION FOR DEPOSITIONAL BASINS OF SILICEOUS IRON-FORMATIONS

BASIN TYPES	LAKE SUPERIOR TYPE	ALGOMA TYPE
TYPICAL BASINS	Lake Superior, Gunflint, Labrador Trough, Belo Horizonte, Transvaal, Hamersley, Cerro Bolivar, Orissa, Kursk, Krivoy Rog	Michipicoten, Mary River, Temagami, Sturgeon Lake, Melville Peninsula, Skibi Lake, Kapico, Lake St. Joseph; Snake River, Red Sea Mud, East Pacific Rise
TECTONIC ENVIRONMENT	EPEIROGENIC Cratonic shelf	OROGENIC Volcanic arcs Extrusive volcanism, Fracture systems; Ocean ridges Rifts, Graben
TECTONIC ACTIVITY	Subsidence Uplift	Deep fracture systems Thrust faults; Tension fractures Rifts, Block faults
BASIN ENVIRONMENT MARINE neritic shelf slope deep ocean		
STABILITY	Stable	Metastable
ENERGY LEVEL	High Low	
CIRCULATION	Restricted Limited	Thermal circulation, Turbidity currents
DEPTH	Shallow Deep	Varied
BASIN SIZE	Large	Small Variable
AGE		
SEDIMENTARY FEATURES bedding texture deformation	Macro, Cross-bedding Micro-laminated Oölitic Breccia, Scour, Slumps	Micro-, Macro-laminated; Irregular Slumps, Crenulated beds; Breccia, Scour
ASSOCIATED VOLCANIC CENTRES close distant		

(Gross 1973, Goodwin 1973, Boström 1970, Piper *et al.* 1975). Whether the constituents of the iron-rich beds are derived directly from differentiation of magma sources or by leaching of elements from crustal rocks by circulation of saline solutions has not been clearly demonstrated. Both processes may be significant contributors of the constituents. Research suggests that circulation of a saline solution of seawater composition would be quite capable of leaching metal and silica constituents from enclosing rocks in sufficient volumes and in the proportion now found in the iron formations (Hajash 1975).

Iron and silica, contributed to depositional basins from hydrothermal effusive sources, are deposited in beds of iron formation through direct chemical precipitation, by flocculation of colloidal and fine particulate iron oxide and silica and by the sedimentary reworking and concentration of the silica–iron-bearing muds and ooze (Gross 1965, 1972). The restriction of other types of sedimentation and the tectonic stability of the basin environments are dominant factors in determining the size, location, distribution and development of facies of the iron formation. The final characteristics of the iron–silica beds are determined by the broad range of conditions and processes operating in a sedimentary basin, no two iron-formations having been deposited in identical environments. Variations in chemical composition of the different iron-formations and their sedimentary facies have been under study for some time and are reported in other papers (James 1966, Gross 1965, Gross & McLeod 1980).

Figure 2 shows some of the major features recognized in the different tectonic environments for iron-formation deposition. It should be noted that a proportionately greater number of iron-formation beds occur in the zone between volcanic centres and the cratonic shelf zone than can be indicated in Figure 2. This area is common territory between the environment models originally designated for Lake Superior and Algoma types of iron formation.

Research is continuing on the possibility of differentiating iron sediments related to (1) thrust-fault systems and (2) graben and ocean-ridge systems. Documentation of the distribution of iron formations in relation to ancient global-scale fracture systems and plate tectonics is of special significance in the understanding and classification of iron-formation occurrences.

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