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Economic Geology, v. 107, pp. 377–380

DISCUSSION

IRON FORMATION: THE SEDIMENTARY PRODUCT OF A COMPLEX INTERPLAY AMONG MANTLE, TECTONIC, OCEANIC, AND BIOSPHERIC PROCESSES—A DISCUSSION

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Sir: Andrey Bekker and co-authors (Bekker et al., 2010) use a holistic approach to the deposition of iron formation (IF) by relating its genesis to a complex interplay of processes within the deep Earth, oceans, and biosphere. They comment (p. 469) that "In contrast to most previous studies, we suggest that no single parameter controlled iron-formation deposition." The word "most" is critical here, since in a *Discussion* of IF genesis in *Economic Geology* nearly half a century ago (Trendall, 1965, p. 1069), I noted the need for a multifaceted approach with the words, "It is useless in any considerations of the origin of iron formation to confine attention to the iron formation itself," and more recently I have discussed, in a paper that has escaped the attention of Bekker et al. (2010), the significance of IF within a wide context of Earth's evolution (Trendall, 2002).

Although I disagree with some of their characterization of the Hamersley Group BIFs of Western Australia, my purpose here is only to comment on their use of IF nomenclature and classification. Their adoption of the simple twofold subdivision of IF, as a rock type, into banded iron formation (BIF) and granular iron formation (GIF), which I first used in the 2002 paper already cited, is admirable. But I suggest that their parallel use of the terms "Superior-type iron formation" and "Algoma-type iron formation" serves more to obscure than to clarify their message.

These names are derived from the classification schemes Gordon Gross developed during the long course of a study, initiated in the 1950s; his focus was the *iron deposits of Canada* (my italics, here and elsewhere in this paragraph); the contiguous deposits of the United States were also included. Gross (1959, p. 89) initially referred to the "Lake Superior or Knob Lake type" as one component (of two) within "Group I" (of six) of his classification of *iron deposits* (i.e., ore deposits); the term "Algoma type" was not used. The criteria for the recognition of the six groups varied widely, but were mainly related to mineralogy and texture. This early scheme underwent substantial transformation, and Gross (1966) later used a fourfold division of *iron-formations* into Algoma type, Superior type, Clinton type and Minette type. The most mature form of Gross's scheme changed from a classification of Canadian *iron deposits* into a "classification of *iron formations* based on *depositional environments*," (Gross, 1980), in which the Clinton type and Minette type are grouped as "ironstones," leaving the "Lake-Superior-type" and the "Algoma-type" as the only two categories of IF. Only generalized criteria were given for the allocation of these labels although, as the title of the paper indicates, the principal criterion was the depositional environment, as deduced from associated rock types. Thus, Gross (1980, p. 215–216) wrote, "The well-known Lake-Superior-type iron formations, widely distributed in Proterozoic rocks, were deposited in near-shore continental environments, and are associated with dolomite, quartzite, black shale, and minor amounts of other volcanic rocks," while the "Algoma-type iron formations, found in all ages of rock, are consistently associated with greywacke sedimentary units." His figure 1, summarizing his scheme in a single octagonal diagram, has the words "Cherty Oolitic" below "SUPERIOR TYPE," and the single word "Cherty" below "ALGOMA TYPE."

In summary, and as emphasized by the italicized words in the preceding paragraph, Gross's terminology evolved from a classification of the iron ore deposits of Canada, based largely on mineralogy, to a classification of the IFs of the world, based on their depositional environment. At no stage were diagnostic, as distinct from descriptive, criteria for application of the names "Superior type" and "Algoma type" to specific IF occurrences clearly specified, and it is unsurprising that there was confusion in their practical application: thus Hamersley IFs were Lake Superior type for Gross (1980, Table 1), but Algoma type for Dimroth (1976).

In 1962, I joined the Geological Survey of Western Australia knowing next to nothing about Precambrian IF. In the same year, I began field and petrographic studies of Hamersley Group BIF, and soon became puzzled by what appeared from the published descriptions to be their clear differences from the IFs of the Lake Superior area; and, as the work progressed, the members of the small team I worked with found it as difficult as I did to slot the Hamersley IFs into any of Gross's categories. In 1966, I was able to spend consecutive months in North America (the United States and Canada) and South Africa, specifically to assess the differences and similarities of the major IFs. I received generous guidance on the ground from geologists on both continents, whose help it was a pleasure to acknowledge in a paper summarizing the results of my visits (Trendall, 1968, p. 1527); it concluded that, "the Western Australian and South African iron formations are very closely similar, but that both differ markedly from the Animikie iron formations of the Lake Superior area" and also that Gross's "distinction between Algoma Type and Superior Type iron formations needs modifications: the granules and oolites described by Gross as typical of Superior Type iron formations are absent from both the Hamersley and Transvaal System Basins, although both these extend for hundreds of miles (Superior Type) rather than for just a few miles (Algoma Type)".

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Over four decades following 1966, it is now clear that the Hamersley BIFs of Western Australia are the largest known IFs on Earth in terms of thickness, areal extent, and tonnes of contained iron; they are also the best exposed, one factor which has led to their more intensive study than any others. It is also well established that there are none comparable in the Lake Superior area, in age, thickness, lateral extent, lithology, depositional environment, and associated rocks. The application of the name Superior type to the Hamersley IFs is as inappropriate today as would be the application of the name Hamersley type to those of the Lake Superior ranges.

Bekker and others clearly realize the difficulties they face in applying these names. For example, on p. 474 they write, "Typical Algoma-type iron formations are less than 50 m thick…". Are they saying here that there are such entities as untypical Algoma-type IFs, and if so, how are the rest of us expected to recognize these as Algoma-type IFs at all? On the next page, they write, "Clear differentiation between Superior and Algoma types of iron formation is difficult in Archean successions affected by strong deformation and shearing …." This description applies to most of the world's greenstone belts, so presumably the Superior/Algoma dichotomy cannot be appropriate for IFs in that setting? The continued use of the terms Superior-type and Algoma-type IFs is bizarre, in face of the facts that neither has ever been properly defined, that the nomenclature evolved over many years of continual change, that study and knowledge of the IFs of the world has advanced enormously since the names were first suggested, and, finally, that their application does nothing to advance the greater understanding of IF deposition that is needed.

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IRON FORMATION: THE SEDIMENTARY PRODUCT OF A COMPLEX INTERPLAY AMONG MANTLE, TECTONIC, OCEANIC, AND BIOSPHERIC PROCESSES—A REPLY

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Sir: We welcome the comments by Alec Trendall (2012) and the chance to clarify statements made in our recent review paper (Bekker et al., 2010). His point of contention is focused on the semantics of iron formation (IF) nomenclature and classification, specifically the validity of, and criteria for, subdivision into Superior, Algoma, granular, and banded types. In addressing his comments, we place this nomenclature and classification into a broader perspective involving the history of IF studies, and then explore underlying genetic controls that formed the foundation for these early schemes.

It is only in the last 40 to 50 years that geology has evolved from a largely descriptive field to one that rigorously applies genetically based concepts founded on detailed understanding of modern processes. In the past decades, our understanding of global tectonics, modern sea-floor hydrothermal processes, geomicrobiology, and process-based sedimentology have advanced dramatically. Studies of iron formations are no exception to this trend. In the 1950s and 1960s, geologists had little knowledge of modern analogues for IF (e.g., sea-floor hydrothermal iron oxyhydroxide deposits and exhalative metal deposits), yet these workers were developing genetic models on the basis of textures, structures, and compositions of iron formations. As a result, various terms and paradigms about IF were introduced that should now be reevaluated in light of insights gained from recent work. Here we list just a few examples of outdated terms and misconceptions. First the term "sulfide-facies iron formation" (James, 1954), which could be sulfidic shale, sulfidic chert, sulfidized iron formation, volcanogenic massive sulfide deposits, or even sulfidized shear zones, should not be considered a subdivision of IF (Bekker et al., 2010). Another example is microbanding that was considered traceable over the full extent of the Hamersley Province for hundreds of kilometers (Trendall, 1968, 2002). It is now recognized beyond any reasonable doubt that this microbanding is not traceable, even on outcrop scale (Krapež et al., 2003). The concept of microbanding (sometimes referred to as "varves"; Trendall, 1973, 2002) became so entrenched in the perception of IF that even some recent studies have attempted to explain its basin-scale extent or apply the concept of microbanding to calculate sedimentation rates. An extreme case of such a model-driven approach—the unsubstantiated emphasis on basin-scale extent of microbanding—led to the widely held view that iron formations have the same thickness throughout the Hamersley Province (e.g., Morris, 1993), despite the fact that isopach maps clearly conflict with this suggestion (Trendall and Blockey, 1970). Another misnomer that was introduced during this early period is podded chert (Trendall and Blockey, 1970), which in actuality is either a chert concretion or a remnant of chert layers replaced by a deformation fabric of anastomosing magnetite (Krapež et al., 2003). Lastly, although earlier studies considered granular iron formation (GIF) to be restricted to the Paleoproterozoic (Trendall, 1968, 2002), it has become increasingly clear over the last 20 years that analogues are also present in Archean settings (Simonson and Goode, 1989; Beukes and Klein, 1990; Spier et al., 2007).

In the Canadian Shield, Gross (1980) recognized two end-members of IF: banded (Fe-oxides, -silicates, and/or -carbonates intercalated with chert) in volcanic-hosted Archean successions (Algoma-type), and granular in sediment-hosted Paleoproterozoic successions (Superior-type). His work placed emphasis, for the first time, on depositional environments when understanding of modern submarine hydrothermal systems was almost entirely lacking. This distinction was very well suited to many Canadian examples, but in a number of cases worldwide its application was ambiguous because multiple intermediate members also exist. Trendall (2012) points out in his comment that this long-standing classification scheme requires reevaluation.

However, while we believe that the strict application of these terms should be used with caution, credit should be given to Gross because he foresaw in these terms what would now be called proximal and distal submarine hydrothermal deposits. Proximal to hydrothermal vents, submarine iron deposits (e.g., jasper and umber deposits in the modern and Phanerozoic oceans) develop in association with volcanic facies, in deep-water, volcanic rock-dominated settings. Hydrothermal plumes rise until they reach buoyancy and, in anoxic water columns, would then extend laterally for hundreds to thousands of kilometers, until they reach shallow-water settings where sedimentary sequences—including IF—are deposited. This distinction is straightforward in modern oceans, where geography is well known, but it is extremely complicated in Precambrian terranes where detailed basin reconstructions are generally lacking.

Clearly, a number of factors, including basin configuration, type of depositional basin, nature of shallow and deep currents, water column and oxygenation, distance from hydrothermal

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vents, and hydrothermal flux and its composition will influence the type of IF deposited. Considering these complexities and uncertainties, one can ask what is the point in making a distinction between these two settings in ancient basins? The answer is clear: because such distinctions are important for understanding ocean and atmosphere chemistry and redox evolution, correlation among unrelated basins on different cratons, and for evaluating the economic potential of iron formations. For example, hydrothermal systems could overwhelm seawater composition and redox state in small, isolated basins such as back-arc basins. In contrast, distal hydrothermal systems that reach open continental margins will be strongly diluted during transport by seawater, and hence are more likely to reflect the composition and redox state of the atmosphere-ocean system. Furthermore, the distal hydrothermal systems that generated significant amounts of iron for upwelling onto open continental margins are likely related to major mantle plume breakout events that affected the composition of the global ocean and led to synchronous IF deposition on several cratons. Thus, these iron formations are important for intercontinental correlations and carry a high economic potential.

So, is the subdivision into proximal and distal submarine hydrothermal systems applicable to IF in the Hamersley Province considering the ambiguity of Algoma- vs. Superior-type classifications as discussed by Trendall (2012)? The well-known Dales Gorge and Joffre iron formations there are hosted in sedimentary sequences. Evidence for contemporaneous volcanism is only recorded by tuffs, volcanic units of the same age are largely absent in those sequences, and layers of carbonate grainstone within IF indicate paleoslopes to the southwest (Simonson et al., 1993). Collectively, such observations suggest that these IFs were deposited distal to submarine-hydrothermal activity. However, in stratigraphically higher units there is clear evidence of spatial and temporal association with volcanic rocks (Weeli Wolli and Boolgeeda iron formations and the bimodal but predominantly felsic Woongarra Volcanics), suggesting a transition toward settings more proximal to submarine-hydrothermal activity.

Discriminating between GIF and banded iron formation (BIF) is more straightforward as it is descriptive and in most cases simply reflects deposition above and below fair-weather wave base, respectively. GIF, common in Paleoproterozoic successions deposited after the Great Oxidation Event at ca. 2.4 Ga (Bekker et al., 2004), is composed predominantly of hematite, indicating that Fe was delivered from the deeper part of the basin and oxidized above the fair-weather wave base. Archean GIF is much less common (Simonson and Goode, 1989; Beukes and Klein, 1990; Spier et al., 2007) and is composed of minerals having reduced or mixed-valence Fe. Biological factors, including water column productivity and Fe and S reprocessing during diagenesis, surely had also a strong impact on the mineralogy and textures of IF.

In summary, distinction between GIF and BIF is descriptive and mainly tells us about water energy and water depth. The terms Algoma- and Superior-type are tied to the proximity of IF to hydrothermal systems. It is essential to acknowledge that there is a complete gradation between Superior- and Algoma-type IF. As stressed above, distinguishing between IF that formed in settings proximal to submarine-hydrothermal vents vs. those deposited distally on open continental shelves is critical, not only for correlating different iron formations and evaluating their economic potential, but ultimately for understanding the evolution of the atmosphere-ocean system. This distinction is not straightforward and requires detailed knowledge of basin evolution and configuration. As an example, recent detailed work has shown that this knowledge can be gained in studies of the Hamersley iron formations (Krapež et al., 2003). As we have tried to stress in our recent review (Bekker et al., 2010), the application of basin analysis and sequence stratigraphy, coupled with insights from geochronology and geomicrobiology, and an understanding of modern submarine-hydrothermal processes, are necessary in order to advance studies of IF. Without these integrative efforts, we are trapped in long-lived myths that carry no relevance to a process-based scientific approach.

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