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Sedimentology, sequence-stratigraphy, and geochemical variations in the Mesoproterozoic Nonesuch Formation, northern Wisconsin, USA

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ABSTRACT

We use core descriptions and portable X-ray fluorescence analyses to identify lithofacies and stratigraphic surfaces for the Mesoproterozoic Nonesuch Formation within the Ashland syncline, Wisconsin. We group lithofacies into facies associations and construct a sequence stratigraphic framework based on lithofacies stacking and stratigraphic surfaces. The fluvial-alluvial facies association (upper Copper Harbor Conglomerate) is overlain across a transgressive surface by the fluctuating-profundal facies association (lower Nonesuch Formation). The fluctuating-profundal facies association comprises a retrogradational sequence set overlain across a maximum flooding surface by an aggradational-progradational sequence set comprising fluctuating-profundal, fluvial-lacustrine, and fluvial-alluvial facies associations (middle Nonesuch through lower Freda Formations). Lithogeochemistry supports sedimentologic and stratigraphic interpretations. Fe/S molar ratios reflect the oxidation state of the lithofacies; values are most depleted above the maximum flooding surface where lithofacies are chemically reduced and are greatest in the chemically oxidized lithofacies. Si/Al and Zr/Al molar ratios reflect the relative abundance of detrital heavy minerals vs. clay minerals; greater values correlate with larger grain size. Vertical facies association stacking records depositional environments that evolved from fluvial and alluvial, to balanced-fill lake, to overfilled lake, and returning to fluvial and alluvial. Elsewhere in the basin, where accommodation was greatest, some volume of fluvial-lacustrine facies is likely present below the transgressive stratigraphic surface. This succession of continental and lake-basin types indicates a predominant tectonic driver of basin evolution. Lithofacies distribution and geochemistry indicate deposition within an asymmetric half-graben bounded on the east by a west-dipping growth fault. While facies assemblages are lacustrine and continental, periodic marine incursions are probable, especially across maximum transgressive surfaces.

We demonstrate a sequence-stratigraphic approach may be applied to fine-grained Precambrian sediments using traditional rock description and supporting lithogeochemistry. Identification of a characteristic lithofacies succession in Mesoproterozoic sediments demonstrates fundamental controls commonly interpreted for Phanerozoic lake systems may be extended into the Precambrian. These controls result in a predictable association of lithofacies, with distinct physical, biological, and geochemical properties. This has regional significance for carbon sequestration and the distribution of mineral and hydrocarbon resources and broader significance for addressing Mesoproterozoic paleogeographic reconstructions and questions related to the evolution of terrestrial life.

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1. Introduction

The latest Mesoproterozoic Nonesuch Formation is part of a thick sedimentary sequence that was deposited within the North American Midcontinent Rift above about 20 km of mostly volcanic rocks (Fig. 1) (Ojakangas et al., 2001). The Nonesuch Formation is the most extensively studied of the rift sediments due to its potential economic significance as a host for metallic and hydrocarbon resources, and as a potential seal for carbon sequestration. In addition, the formation is the focus of fundamental research into environmental controls on the expansion of terrestrial life (Cumming et al., 2013; Gallagher and Sheldon, 2014).

Previous studies have interpreted both marine and lacustrine depositional settings for the Nonesuch Formation. Hieshima and Pratt (1991) and Pratt et al. (1991) interpret a marginal marine

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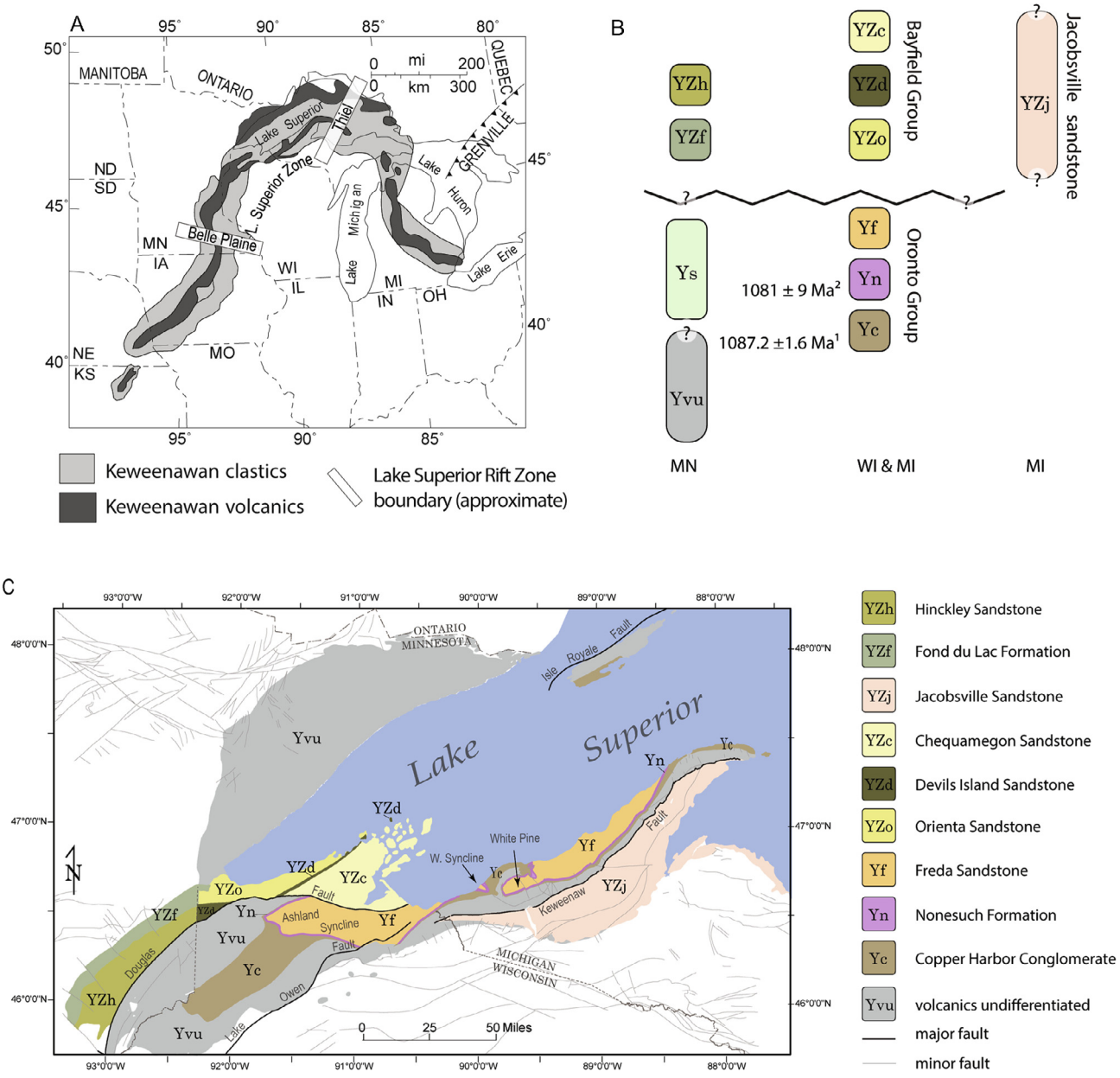

Fig. 1. Regional setting of the Midcontinent Rift System: A. Generalized bedrock geologic map of the Midcontinent Rift System. The Nonesuch Formation was deposited within the Lake Superior zone of the rift, in northern Wisconsin and the Upper Peninsula of Michigan. Modified after Dickas and Mudrey (1997) and Ojakangas et al. (2001). B. Correlation of map units for the Keweenawan Supergroup. [1]U-Pb age from zircon sampled from an andesite flow in the Copper Harbor Conglomerate (Davis and Paces, 1990); [2] Pb-Pb isochron age from a carbonate bed near the base of the Nonesuch Formation, Western Syncline (Ohr, 1993). Modified from Ojakangas et al. (2001). Abbreviations are as follows: MN: Minnesota, WI & MI: Wisconsin and Michigan, MI: Michigan, Yvu: Mesoproterozoic volcanics undifferentiated, Yc: Mesoproterozoic Copper Harbor Conglomerate, Yn: Mesoproterozoic Nonesuch Formation, Yf: Mesoproterozoic Freda Formation, YZf: Meso-Neoproterozoic Fond du Lac Formation, YZo: meso-Neoproterozoic Orienta Sandstone, YZd: meso-Neoproterozoic Devils Island Sandstone, YZc: meso-Neoproterozoic Chequamegon Sandstone, YZj meso-Neoproterozoic Jacobsville Sandstone. C. Regional bedrock geologic map for the Lake Superior Region locating the Ashland syncline, Western Syncline, and White Pine areas. The Copperwood area is located within the Western Syncline. Modified after Cannon et al. (1999) and Ojakangas et al. (2001).

depositional environment based on sulfur/carbon ratios, total sulfur content, and the composition of organic matter. Imbus et al. (1992) favor lacustrine deposition and suggest potential biologic, sedimentologic, diagenetic, and post-diagenetic controls on organic, elemental, and stable isotopic properties of the Nonesuch Formation. Elmore et al. (1989) and Suszek (1997) interpret lacustrine facies assemblages from regional sedimentological descriptions of the unit based on observations of core and outcrop in Wisconsin and Michigan. Cumming et al. (2013) also favor a lacustrine setting based on Os isotope data.

Despite these previous studies, the Nonesuch Formation's detailed sedimentology and stratigraphy remains relatively unstudied, and the Formation has never been interpreted within a genetic framework. The absence of a detailed, sequence-stratigraphic framework, despite significant past and ongoing research, reflects the difficulty in correlating Precambrian sediments in the absence of diagnostic trace and body fossils. Previous stratigraphic and sedimentologic interpretations were lithostratigraphic, as the sequence-stratigraphic method (e.g., Mitchum and Van Wagoner, 1991; Neal and Abreu, 2009) especially for