SEQUENCE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE CRETACEOUS AGRIO FORMATION OF THE NEUQUEN BASIN

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ABSTRACT

The Lower Cretaceous Agrio Formation of the Neuquén Basin of Argentina is the youngest marine source rock in the basin, however, its potential as an unconventional resource is poorly understood, with only a few recent wells on production from this developing play. The Jurassic-aged Vaca Muerta Formation has been the main unconventional target in the Neuquén Basin due to its world-class source rock and unconventional reservoir characteristics. In order to assess the economic potential of the Agrio as a secondary unconventional target, a detailed surface to subsurface characterization was undertaken to better understand reservoir potential. The first step in characterization of these unconventional reservoirs is through the construction of a robust sequence stratigraphic framework in order to hydrocarbon play element presence, quality, and distribution.

A sequence stratigraphic framework for the Agrio Formation was developed based on stratal geometry, stratal architecture, stratal terminations, stacking patterns, and facies associations as determined via outcrop, seismic, well-log, and core data. Through this integrated approach a genetic framework was established and subdivides the Agrio Formation into three distinct genetically related members (i.e., lower, middle, and upper), with each subdivision representing characteristic stratal geometry, stacking patterns, and facies associations at the sequence-set scale. The lower Agrio encompasses a transgressive to highstand sequence set with optimal source rock and unconventional reservoir quality focusing near the 2nd order maximum flooding surface (mfs). The middle Agrio is of key importance, not in terms of unconventional reservoir potential, rather, due to the regional unconformity at the base of the interval that superimposes non-marine strata above distal offshore mudstones. This unconformity is a 2nd order sequence boundary (sb) and overlying lowstand sequence set that erodes into the underlying lower Agrio target, thus identifying this boundary is critical to constrain reservoir extent. The upper Agrio reflects similar genetic trends observed in the lower Agrio, representing a transgressive to highstand sequence set with a secondary unconventional target developing below the 2nd order mfs as the system progrades into the basin. This hierarchical framework better documents spatial and temporal variations at the scale necessary to predict reservoir quality and distribution to identify potential target intervals within this unconventional system.

INTRODUCTION

Exploration of tight (unconventional) plays in the Neuquén Basin has recently been a prioritized focus for the energy industry, with multiple organic-rich facies present throughout the stratigraphic column. The vastly explored Vaca Muerta of the Neuquén Basin is the primary unconventional target, representing the first economical unconventional play outside of North America (Minisini *et al.* 2020; Reijenstein *et al.* 2020). Through continued exploration efforts, secondary and tertiary targets (e.g., Agrio and Los Molles Formations) were also identified. Although there is significant economic potential for these additional unconventional benches, the lack of data and detailed geologic characterization hinder the ability to assess hydrocarbon potential (i.e., EUR) and spatial distribution of hydrocarbon play elements.

Key controls on unconventional reservoir quality and distribution in fine-grained, mudstone-dominated successions include total organic carbon (TOC), organic matter type (e.g., Type I-II liquid prone, Mixed Type II/III, or type III gas prone), mineralogy (i.e., clay content/ductility, brittleness, "fracability"), presence and distribution of high-strength rocks (i.e., fracture barriers/baffles), thermal maturity (0.8–1.3 for liquids-rich play), porosity/permeability, presence and distribution of natural fractures, and thickness of pay interval (Bohacs *et al.* 2005; Gale *et al.* 2014; Passey *et al.* 2010; Schieber and Wilson 2013; Wilson and Schieber 2016; Wilson *et al.* 2020, 2022; Katz *et al.* 2021; Venieri *et al.* 2021).

Unconventional resources show characteristically low permeabilities, which is directly a result of textural attributes and composition (particle diameter <62.5 μm), diagenetic alteration (i.e., secondary precipitation of void-filling clays and cements), as well as small-scale vertical and lateral heterogeneity (i.e., bedding styles and continuity, facies change, geobody distribution, diagenetic alteration or emplacement). Therefore, it is necessary to employ fundamental sedimentologic and stratigraphic workflows in combination with organic and inorganic geochemical data to develop a robust geologic model for prediction of hydrocarbon play elements at an exploration-scale (regional), as well as play element variation at the well-pad scale (landing-zone variation). Through surface and sub-surface characterization, data and interpretations regarding stratigraphic architecture, lithofacies variation, compositional trends, and total organic content can be evaluated and mapped to develop a fully integrated sequence stratigraphic model (Bohacs *et al.* 2005). Furthermore, proximal–distal relations within the geologic system can be better understood for identifying distribution and richness of potential target zones for exploration and development.

METHODOLOGY

The current investigation focuses on an integrated sequence stratigraphic framework developed through the combined observations from surface exposures that are representative of subsurface data from neighboring fields (i.e., Loma Campana and El Trapial), drill cores, wireline logs, and available seismic data (Fig 1). Detailed lithologic profiles were collected at each outcrop locality. Outcrops also provide key sources for biostratigraphic sub-divisions in previous studies that facilitated surface to sub-surface correlations of genetic framework (Pazos

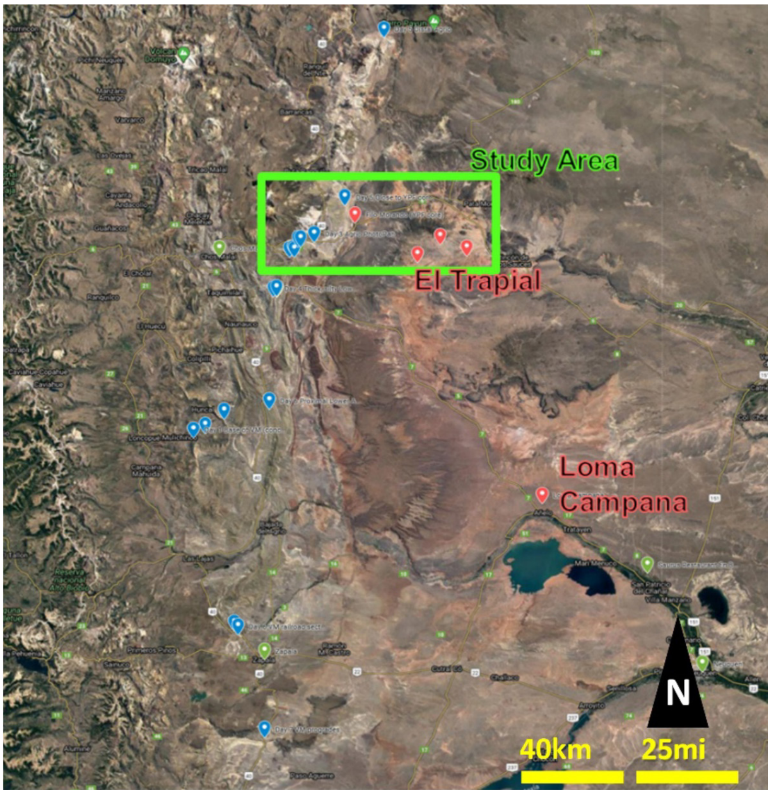

Figure 1. Overview map of all field locations for this study (blue highlighting outcrop locations, red highlighting Chevron field locations).

et al. 2020). Observations of texture, sedimentary features, bioturbation index, ichnogenera, diagenetic overprint, bed thickness, shape and continuity were recorded at outcrops as well as at drill core locations. Drill core preserve more depositional textures due to the lack of exposure to weathering, whereas outcrops facilitate the characterization of 3-dimensional stratigraphic architecture, stacking patterns, stratal terminations and key surfaces, as well as bedset-scale relations and trends. Moreover, surface exposures aid the inquiry of depositional processes and systematic characterization of transport mechanisms, especially in the context of flow evolution and lateral variability of depositional elements. Through variable lighting, as well as wet vs. dry imaging, detailed image sets of sedimentary features at the hand specimen scale were acquired.

Seismic and well log data were utilized to capture surface to subsurface characterization, especially in the context of sequence stratigraphy. Through applying fundamental sequence-stratigraphic principles, sedimentary successions can be differentiated into a chronostratigraphic framework based upon stratal architecture, stratal geometries, stratal terminations, stacking patterns, and facies and facies associations (Van Wagoner 1988). Once a genetic framework is developed, inferences regarding sediment delivery, accommodation, and shoreline trajectory enables prediction away from data control (Bohacs *et al.* 2005; Donovan and Staerker 2010). Through the development of a fully integrated sequence-stratigraphic framework and incorporation of surface and subsurface data, hydrocarbon play element quality and distribution can be evaluated, which is critical for economic success.

Although it is not necessary to know the forcing mechanisms of sequence formation to construct a sequence-stratigraphic framework and map the distribution of rock properties, it is commonly useful to incorporate one's understanding of key processes to provide predictive capabilities away from sample control. Many factors influence the development and expression of parasequences and depositional sequences, but these factors devolve into two main proximate controls: the rate of accommodation change relative to the rate of sediment supply. There are several methodologies for employing genetic basin analysis, for this study, the Exxonian sequence stratigraphic model is utilized (Van Wagoner *et al.* 1988). In this model, the depositional

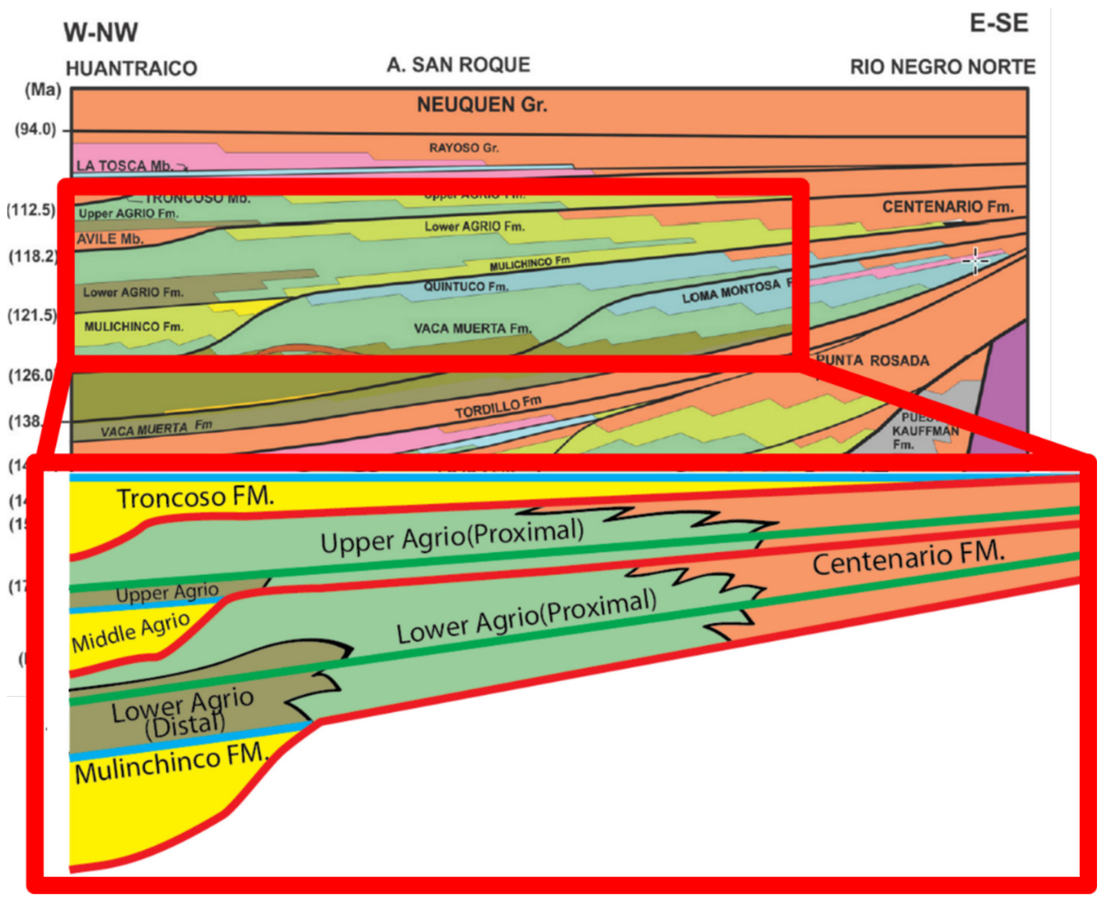

Figure 2. Conceptual cross-section of the Neuquén Basin (after Schwarz *et al.* 2016) with a box highlighting the sequence stratigraphic framework developed for the Agrio Formation, respectively. The formation names (e.g., Mulinchinco, Centenario, Lower Agrio (proximal-distal), Middle Agrio, Upper Agrio (proximal-distal), Troncoso) represent lithostratigraphic distinctions. The sequence stratigraphic interpretation is overlain this cross-section with key stratigraphic subdivisions (red lines are sequence boundaries, blue lines are transgressive surfaces, green lines are maximum flooding surfaces). This framework subdivides this gross interval into multiple sequence sets composed of Lowstand, Transgressive, and Highstand intervals, respectively. The interpretations of this framework implemented correlations at multiple scales, with key observations at field exposures to delineate stacking patterns, facies associations, and stratigraphic architecture (see Fig 4). Regionally the time equivalent strata span a siliciclastic-dominated system where siliciclastics are being shed from the south to the north (see Fig 3). A local carbonate factory is developed during transgressive episodes in the lower and upper Agrio formation which primarily delivers calciclastics in the distal realm of the Agrio.

sequence is the primary stratigraphic unit and is composed of three (3) systems tracts with characteristic parasequence stacking patterns and architecture (i.e., lowstand systems tract (LST) with progradation to aggradation parasequence stacking, transgressive systems tract (TST) with retrogradation parasequence stacking, and highstand systems tract (HST) with progradation to aggradation parasequence stacking). Moreover, three (3) effectively isochronous stratigraphic surfaces (i.e., sequence boundary (sb), transgressive surface (ts), and maximum flooding surface (mfs)) are identified and correlated where stacking of parasequences change, representing a significant shift in shoreline trajectory and depositional environments.

System tract boundaries are identified through correlation of parasequences and termination styles of parasequence boundaries (onlap, downlap, toplap, or truncation). Through mapping vertical and lateral expression of parasequences, parasequence-set-scale observation provide the key inputs for evaluation at the depositional sequence scale (i.e., LST, TST, HST). It is at the depositional sequence- and sequence-set-scale where observations and analysis can be validated at the scale of reflection seismic data (10’s of meters).

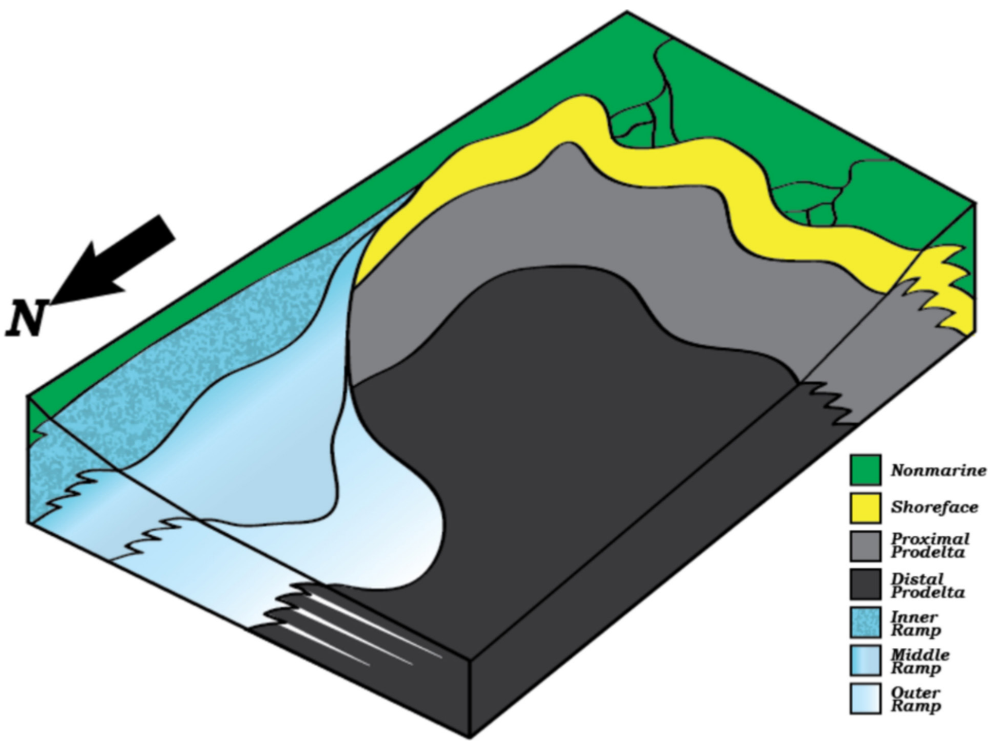

Figure 3. Depositional model for the Agrio Unconventional system, highlighting a southerly siliciclastic source area and an easterly carbonate factory that delivers calciclastics into the basin. This represents a shoreline-attached depositional system with shallow marine siliciclastic distributed from the south which dilutes organic-matter content of the source-rocks to the north. Similarly, the carbonate system to the east (when active) dilutes organic-matter content of the key source-rock intervals.

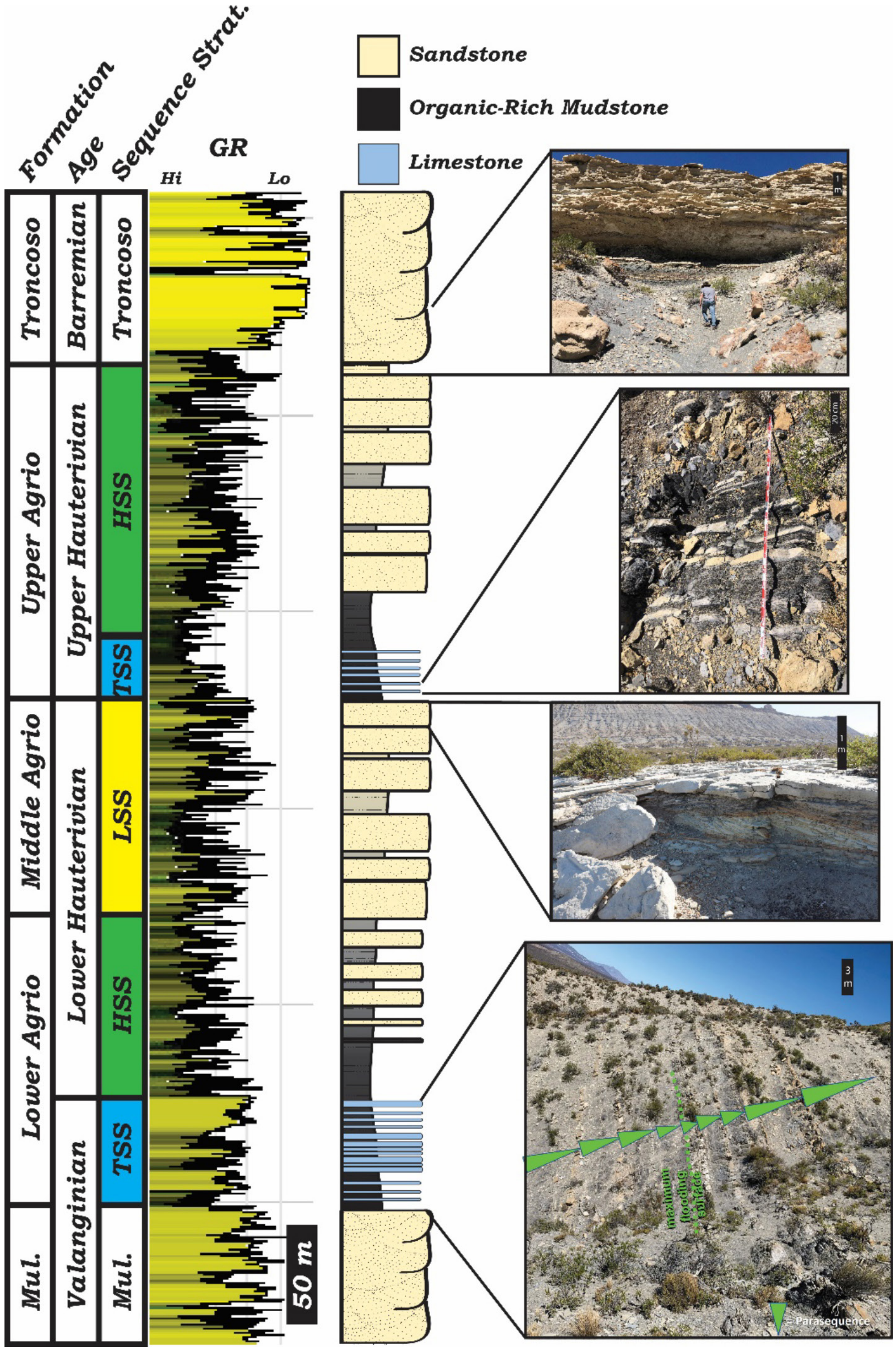

Figure 4. Type-log for the Agrio Unconventional system, with a Total Gamma-Ray (GR) log (left) and key sequence stratigraphic stratigraphic intervals (LSS=Lowstand Sequence Set, TSS=Transgressive Sequence Set, HSS=Highstand Sequence Set) with corresponding lithostratigraphic formation and age. To the right of the GR log is a lithologic column from an outcrop characterized for this project and overview images of key intervals and stratigraphic contacts. Starting at the basal TSS of the Lower Agrio, we observe a interbedded organic-rich mudstones and fine-grained limestones with high vertical heterogeneity. The HSS of the Lower Agrio marks a basinward migration of the shoreline above the mfs as the siliciclastic system progrades to the north. The Lower Agrio HSS is capped by a regional unconformity that superimposes non-marine (coastal plain and fluvial) mudstones and sandstones (note the highly serated GR signature of this interval characteristic) of the traditionally called "Avile" Member, and represents a lowstand sequence set (LSS). The Upper Agrio shows very similar trends to the Lower Agrio, with a basal TSS containing organic-rich calcareous mudstones that transition vertically into an HSS with silty and sandy mudstones and another regional sb with the overlying Troncoso Formation.

RESULTS

Through the integration of surface and subsurface data, the Agrio Formation herein is subdivided into 2 distinct composite sequences that provides insights into the prediction of optimal reservoir quality development in time and space (Fig. 2). This depositional model was developed through investigating facies distribution within the genetic framework and translating spatial trends to improve prediction of reservoir properties away from well control. The Agrio represents a mixed-depositional system with multiple sediment inputs that strongly controls the organic-matter enrichment (up to 10 wt%), thus, capturing regional trends in deposition is key for prediction away from data control. The Agrio Formation can be correlated to coeval shallow-marine, transitional, and non-marine strata to the south (e.g., Centenario Formation).

The Lower Agrio show a basal organic-enrichment with retrogradational stacking patterns (from the parasequence- to sequence-scale) that are characteristic of transgressive sequence set (TSS; Fig 4). A regional mfs is identified at the top of the TSS which marks the most landward position of the shoreline and the most regional extent of organic-rich calcareous facies. Above this mfs, the Lower Agrio shows a dominantly progradational expression in seismic, which manifests as several coarsening upwards packages in 1-D well logs and outcrops/core (Fig 4). Furthermore, organic-rich calcareous mudstones of the TSS transition vertically into silty and sandy mudstones, indicating a basinward migration of the shoreline during the highstand sequence set (HSS). The Lower Agrio is capped by a regional unconformity that is expressed in seismic by regional truncation below and onlap/downlap termination style above. Above this regional sb is designated as the Middle Agrio which is composed as coastal plain and fluvial sandstones of the traditionally called "Avile" Member, and represents a lowstand sequence set (LSS). This sb is very difficult to identify in well logs due the the serrated gamma ray signature of coastal plain mudstones that overlie marine mudstones of the Lower Agrio. However, this is the most important stratigraphic surface throughout the basin as it erodes into the optimal Lower Agrio interval, and signifies a drastic change in the deposition throughout the basin. The Upper Agrio shows very similar trends to the Lower Agrio, with a basal TSS containing organic-rich calcareous mudstones that transition vertically into an HSS with silty and sandy mudstones and another regional sb with the overlying Troncoso Formation. However, the Upper Agrio shows a more proximal system compared to the Lower Agrio, with increased clastic dilution that reduces the thickness and organic-carbon content.

CONCLUSIONS

Through this integrated sequence stratigraphic characterization of the Agrio Formation, spatial and temporal variance in rock properties and reservoir quality can be predicted and propagated between data control. Furthermore, trends in rock properties associated with depositional environments can be utilized in static and reservoir modeling during exploration and asset development, especially when lacking data control. Characterization across various scales of observation (i.e., Seismic to thin-section) is necessary to capture variance in rock properties across scales. Furthermore, with a genetic understanding of this system we can more accurately select analogs with similar genetic relations.

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