Recommendation for A Practical Log-based Stratigraphic Framework for the Kurdistan Region of Iraq*

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Abstract

Significant inconsistency exists in designating lithostratigraphic units and nomenclature usage for subsurface stratigraphy among Kurdistan operators, resulting in adverse business impacts. Using well log and lithology data from recently drilled wells provided by the MNR (Ministry of Natural Resources) of KRG (Kurdistan Regional Government), three composite reference sections were generated for the north, central and south subregions of KRI (Kurdistan Region of Iraq), respectively. In addition, representatives from major Kurdistan operators and the MNR have collectively built consensus on log-based pick criteria for 14 key stratigraphic horizons, which are sequence-chronostratigraphy in nature and can be easily and consistently picked and correlated across the KRI. These key surfaces and associated megasequences are graphically illustrated with real log curves, and their pick criteria are concisely summarized. Historical lithostratigraphy names have been maintained while some lithostratigraphy units are grouped and elevated to group status to indicate a close genetic relationship (i.e., depositional megacycle). With these 14 horizons serving as anchor points for regional correlation and calibration, the Kurdistan operators will have a common ground for data-sharing while continuing to benefit from the flexibility for making picks at subordinate levels when dealing with specific field or reservoir-scale stratigraphic intervals. The reference materials provided in this report will lead to a more consistent subsurface lithostratigraphy framework and benefit all Kurdistan operators. It also becomes clear that future study on Kurdistan subsurface stratigraphy should focus on clear and unified designation of fundamental lithostratigraphy units (i.e., formations), their log characters, high-resolution chronostratigraphic control, regional lithofacies variation, and integration with seismic survey data. This will lead to a deeper understanding of facies relationship, sequence stratigraphy architecture, reservoir quality and distribution, and ultimately to the establishment of refined unified regional and sub-regional stratigraphic framework(s).

Introduction

The current Kurdistan stratigraphy framework is largely based on outcrops exposed in the Zagros and early exploration wells drilled prior to 1950s, mostly in the Mesopotamian Basin. Most of the lithostratigraphy units were established over half a century ago and initially documented in unpublished TPC/IPC (Turkish Petroleum Company established in 1912 was renamed Iraq Petroleum Company in 1929) company internal reports. Results of these studies were later summarized and made publically available with the publication of the monumental LSI (Lexique Stratigraphique International or Stratigraphic Lexicon of Iraq; van Bellen et al., 1959). Although later workers (e.g., Chatton and Hart, 1960, 1961; Buday, 1980; Jassim and co-authors in Jassim and Goff, 2006; Aqrawi et al., 2010; among many others) have refined, revised, and reinterpreted some existing lithostratigraphy units or even established some new units, the stratigraphy framework published in the LSI remains the primary reference for the entire country of Iraq, including the KRI (Kurdistan Region of Iraq).

Increased exploration activities in the past decade in the KRI have led to influx of new data. Especially, drilling of deep exploration wells with modern logging tool suites and seismic survey generated new types of data covering areas where no wells had previously been drilled, allowing high-resolution stratigraphic correlation and tracking of depositional styles and facies variation. Meanwhile, new data from different facies belts and a diversity of operators have inevitably resulted in increased discrepancy in applying and interpreting existing stratigraphic nomenclature. Inconsistent stratigraphy framework and practice have resulted in adverse impacts on business and operations, and there is need for consensus both in nomenclature usage and recognition criteria. In light of such issues, a stratigraphy workshop was held on August 3-4, 2016, in Erbil on behalf of the MNR aiming to bring the operators together to collectively construct a consistent stratigraphic framework that can be used in practical applications for current and future operations in the KRI.

Most of the Paleozoic to Middle Jurassic stratigraphic units are regionally homogenous and separated by natural breaks, i.e., depositional hiatuses. They can be correlated across the entire region based on log and lithologic characters with high confidence. Facies variation and lithologic heterogeneity become more obvious for Upper Jurassic and younger sediments where only major sequence boundaries are prominent across the entire region. Significant facies variation led to establishment of sub-regionally restricted lithostratigraphy units and correlation of these units across the entire region based on log characters alone is often less unambiguous.

In this study, pick criteria are presented for recognizing major lithostratigraphy boundaries with easily recognized log characters, obvious lithologic change, and major sequence boundaries or their correlative surfaces (Figure 1). Lithology and log-based pick criteria for 14 key surfaces as major anchor points for stratigraphic correlation and calibration are recommended and illustrated with real well data from the KRI. Operators drilling various stratigraphic intervals in different areas to target specific reservoirs may need to subdivide these megasequences into subordinate units with higher order surfaces based on appropriate criteria. This flexibility is necessary for successful operation, and it provides convenience for internal communication; however, it is not possible to practically enforce across the entire region. The 14 key surfaces discussed in this work provide a robust framework for confining and calibrating strata at subordinate levels, allowing easy communication and data-sharing while permitting individual flexibility at field and/or reservoir scale.

It must be noted, however, that the sole purpose of this work is to provide unified, consistent, practical and log-based pick criteria and graphical references for major lithostratigraphic surfaces with real examples from wells in the Kurdistan Region of Iraq. It is not an attempt to do lithostratigraphy or sequence stratigraphy study, though these should be the focus of future work.

Database

The framework is presented as three composite type sections representing the north, central and south regions of the KRI, with each section being constructed from 3-4 wells within the respective subregions (Figure 2). The framework focuses on practical recognition of major lithostratigraphic boundaries, and reference sections have been developed to remove any structurally altered thicknesses, such as repeat sections. Not all data were available to allow all dip-related stratal thickness to be restored back to true stratal thicknesses. Nevertheless, all picks are lithostratigraphy horizons based on log characters and lithologic change; stratal thickness should not be considered as a major criterion for picking lithostratigraphic boundaries, though comparing log curve trends and stratigraphy contexts is always an essential practice for conducting log correlation.

This work will present pick criteria for the key lithostratigraphic surfaces identified, which are primarily based on wireline log characters, recognizing that these are the primary data used for real-time operational decisions and post-drill analysis. In some cases, a significant boundary is poorly defined on wireline log data alone and requires additional data that is not always available to every operator, such as biostratigraphic, radiometric, and strontium stable isotope age data, to define the surface. In these cases, references are provided as additional criteria. The framework has been kept at a high level to avoid field specific differences in pick criteria.

The northern composite reference section is made from 3 exploration wells (Well 1-3) in the area northwest of the Greater Zab River (Figure 2). It represents the most comprehensive section (from Ordovician to Neogene) among all three composite sections. The deep section beyond the Middle Triassic has largely been unpenetrated outside of the northern area.

The central composite is made from splicing two wells (4 and 5) north of the Little Zab River with reference to a third well (6) south of the Little Zab River (Figure 2). The south composite is spliced from four sections (Well 7-10, and two sidetrack sections in Well 7) in the SE Kurdistan High Zagros. Both the central and south composite sections have terminated in the Upper Triassic. The Upper Triassic to Middle Jurassic can be readily correlated with the North Composite (Figure 3). The Cretaceous and Paleogene in central and south composite sections exhibit significant stratal thickness and log character change between equivalent intervals from the northern region due to facies variation. These differences will be discussed in the following respective sections.

Stratigraphy Inconsistency

Prior to 2003, there was very limited exploration drilling activity in the Kurdistan Region, resulting in a paucity of subsurface technical data specific to the significant discoveries in older sediments. In addition, there was virtually no seismic data collected, and when wells and seismic data were available, they came generally from areas in or close to the existing oil fields, such as the Kirkuk area, and avoided the more mountainous regions (Mackertich and Samarri, 2014). Moreover, getting access to existing subsurface data is often extremely difficult. Therefore, much of the subsurface stratigraphy continues to be based on field observations and unpublished IPC internal reports on a few early (1930-1950s) exploration wells summarized in the LSI (van Bellen et al., 1959), which has proven to be an invaluable source of data on the lithostratigraphy of Iraq.

The Kurdistan outcrops played a major role in the establishment of Iraqi stratigraphy published in the LSI (van Bellen et al., 1959). According to LSI, the Iraqi stratigraphy framework is composed of over 60 lithostratigraphy units. Among them, over 40 are from outcrops exposed in Kurdistan, the remaining are either from outcrops in the rest of Iraq, or wells mostly from the lowlands (predominantly South Iraq) drilled in the 1930-1950s (van Bellen et al., 1959). Outcrops have great advantage for understanding the stratigraphy in many aspects. However, they are often very difficult to correlate with subsurface sections for lack of well logs and with little visual graphic illustration. Missing or repetition of an interval due to incomplete exposure or shift of section and obscuring lithology due to subaerial diagenesis, especially dissolution of evaporites, are additional obstacles.

Subsurface sections, especially those described from old wells, pose their own challenges. Low-quality log data, commonly with only SP (spontaneous potential) and RES (resistivity) curves in old IPC wells, and structural complexity make it even more difficult to correlate between outcrop and subsurface sections. Data restriction and quality limitation in addition to individual experience have led to inconsistent stratigraphy nomenclature and practice. Figure 4 illustrates examples of inconsistent lithostratigraphy frameworks extracted from reports of various operators, and Figure 5 demonstrates a real example of two competing lithostratigraphic frameworks for the Lower-Middle Jurassic interval in Well 1.

Obviously, an inconsistent lithostratigraphy framework and practice will have adverse business impacts: communication and data sharing among co-venture partners and between operators and government agency, in addition to asset assessment, drilling operations, and field development. Consequently, there is need for a consistent and log-based practical stratigraphy framework for correlation. Influx of new and high quality subsurface data in the last decade makes this needed improvement possible. The next section describes and illustrates pick criteria for 14 major stratigraphy surfaces with three regional reference sections based on modern log data, lithologic characters, and sequence stratigraphy interpretation, with biostratigraphic and strontium stable isotope age constraints as supplementary criteria. Except when dealing with synonyms or ambiguous description, every effort is made to honor the historical definitions of lithostratigraphy units and stratigraphy framework established in the LSI (van Bellen et al., 1959) and subsequent revisions (Chatton and Hart, 1960, 1961; Buday, 1980; Jassim and co-authors in Jassim and Goff, 2006; Aqrawi et al., 2010; among others). Interested readers should refer to these materials for description of type sections and historical evolvements.

Stratigraphy Surfaces and Pick Criteria

Key stratigraphy surfaces are selected based on their regional consistency, sequence and tectonostratigraphic significance, and economic importance. A major stratigraphic package is genetically related and bounded by two surfaces. In most cases, a surface represents a major change in depositional style reflecting either a major reversal of eustatic trend or a particular phase of tectonic evolution. In fact, most key surfaces discussed in this work are megasequence boundaries, i.e., major hiatuses or their correlative surfaces. Each surface will be discussed as it is related to its stratigraphic significance and pick criteria. Three concise summary tables are provided for recommended pick criteria (based on log characters, lithology, lithofacies, age constraints, and sequence stratigraphic significance, etc.) for the most commonly picked lithostratigraphic units.

To graphically demonstrate characteristics of each major surface, well log curves and lithology interpretations are illustrated. As shown in Figure 5, the first track of log curves contains GR (Gamma Ray) and SP (Spontaneous Potential) logs. The second track includes resistivity (RES: RESD for deep and RESS for shallow resistivity) curves. The third track displays the DTC (compressional wave travel time) and RHOB (neutron density). For some wells, one or more types of log data for part or the entire section is missing. In addition, log-curve variation should be considered as qualitative since casing and different logging tool suites likely affected absolute value. The lithology interpretation track may include one of three types of derived lithology data. One of them is lithology derived from mineral composition (clay, dolomite, calcite, and anhydrite) calculated from well logs (e.g., the Paleozoic-Jurassic in the north composite). Another is lithology description from ditch cuttings (central and south composite sections). The last is petrographic observation from thin sections either from sidewall cores or most commonly from cuttings at 10-15m composite sample spacing (e.g., the Cretaceous and Paleogene in the north composite). Lithology/mineralogy legends are labeled on the right column in Figure 5 and followed by all other figures in this work.

Chia Zairi Formation

Only a few deep exploration wells in Kurdistan penetrated the entire Chia Zairi Formation. Chia Zairi Formation was established in an outcrop on the north flank of the Ora Fold in North Kurdistan, where it attains a thickness of 811m. Its upper contact with the overlying Mirga Mir Formation is continuous; however, it is marked by a lithologic change from clean limestone to argillaceous carbonate. At the base of Chia Zairi Formation is a prolonged hiatus separating the basal transgressive shale from the underlying carbonate of the Harur Formation (van Bellen et al., 1959), as the Ga'ara terrestrial sandstone is absent from Kurdistan. Its contact with the underlying Harur Formation is a hiatus and a change from clean carbonate with low GR and high RES to silty-calcareous claystone with high GR, low RES, and low RHOB. The top of Chia Zairi Formation is a consistent log-curve pick from a clean limestone with low GR, high RES, and fast DTC to the claystone or argillaceous carbonate at the base of Mirga Mir Formation with higher GR, lower RES and slower DTC. The well log criteria and lithology characters are illustrated in Figure 6 and summarized in Table 1.

The Chia Zairi Formation is 900m (MD – measured depth) in Well 2, but decreases to 655m in Well 1. It is composed of three argillaceous-sandy to clean carbonate cycles with decreasing gross thickness (Figure 6). The chronostratigraphic range of the formation is from Middle Permian to the Induan Stage of the Lower Triassic (Jassim et al., 2006).

Geli Khana Formation

The Geli Khana - Kurra Chine contact in the type section (Ora outcrop in North Kurdistan) is a disconformity with "a 3.5m thick laminated ferruginous dolomite with streaks of black chert and nodular hematite" (van Bellen et al., 1959). This may be easily observed in outcrops but difficult to recognize in subsurface. Therefore, the pick for the top of Geli Khana Formation is often inconsistent: at the base of anhydrite of the overlying Kurra Chine Formation or at the contact between the thinly bedded carbonate and massive, clean limestone. The former is a sequence stratigraphic approach (sequence boundary), and it is more easily recognized from log curves (change from low and serrated GR to clean, low GR, and low to very high RHOB) and lithology description. The latter approach is an economic consideration, i.e., to place the carbonate seal-anhydrite reservoir pair in the same lithostratigraphy unit - the Kurra Chine Formation. Most of the Kurdistan Stratigraphy Workshop participants prefer to adopt the latter approach (A), though all agree that the base of the anhydrite is a more significant sequence stratigraphic surface (B) (see Figure 8). This study presents both alternative scenarios to represent the group decision and the preference of the authors of this work.

The basal contact with the underlying shale of the Beduh Formation is recognized from well log as a higher GR, higher RES, and faster DTC due to increase in carbonate. The upper contact with the basal Kurra Chine Formation is a change from low and clean GR and low RHOB to higher serrated GR and increase in RHOB (scenario A). The lithologic and log characters of the Geli Khana Formation and the stratigraphic contexts are graphically illustrated in Figure 7 and summarized in Table 1.

The Geli Khana Formation is 575m in the outcrop type section. With the current definition (scenario A), the thickness of the formation in subsurface ranges from 471m in North Mesopotamian Basin (Atshan-1) to 610m in Well 1 and up to 905m (unadjusted MD) in Well 2 in north Kurdistan. The formation can be conveniently subdivided into the lower and upper parts. The lower part is argillaceous to sandy carbonate with thin anhydrite interbeds, and the upper part is clean and massive carbonate.

The Geli Khana Formation is widely considered as restricted to the Middle Triassic (van Bellen et al., 1959; Aqrawi et al., 2010). This is confirmed by the earliest Carnian strontium age for the basal Kurra Chine anhydrite in North Iraq and Syria (Grabowski and Liu, 2010).

Kurra China Formation

The Kurra Chine Formation was also established from an outcrop on the north flank of the Ora Fold in North Kurdistan (van Bellen et al., 1959), and it was reached in several exploration wells across Kurdistan.

The upper contact with the overlying Baluti Formation is a major lithologic change from massive or interbedded anhydrite and carbonate with low GR, low RES, high RHOG, and fast DTC to black shale-anhydrite-carbonate interbeds with high GR, low RHOB, and slow DTC (Figures 8 and 9). This can be correlated across the region. The contact is more gradational in central and south regions than in north Kurdistan. The pick criteria are illustrated in Figures 8 and 9, and summarized in Table 1.

The thickness of the Kurra Chine Formation is 834m in type section. In subsurface, it ranges from 742m to 1036m (all MD) in north and central Kurdistan. The thickest is 1327m in Well 1 where a section is likely repeated. When thickening from dipping or repetition is adjusted, the true thickness of the formation ranges from 700m to 950m in Kurdistan, though it may reach over 1700m (MD and unadjusted) in some Mesopotamian basin wells according to Jassim et al. (2006). Caution should be applied when extreme thickness occurs in structurally complex region, such as Kurdistan. Nevertheless, restoration to true thickness requires additional data, such as dipmeter reading, seismic survey, borehole image, and stratigraphic correlation. Very often, such data are not available.

The age of Kurra Chine Formation is suggested to be Late Triassic by van Bellen et al. (1959). Aqrawi et al. (2010) revised it to Carnian-Norian age. Strontium stable isotope age-dating of the formation by Grabowski and Liu (2010) produced earliest Carnian age for the basal anhydrite and middle Norian age for the upper anhydrite from wells in North Iraq and Syria.

Baluti Formation

The Baluti Formation was also established based on a north Kurdistan outcrop (van Bellen et al., 1959). The top of Baluti Formation is a regional marker, obvious lithologic change from underlying coastal plain shale or marginal marine shale-carbonate interbeds to shoal carbonate of the basal Sarki Formation. The log characters for the Baluti Formation include serrated and low GR, low RES, low RHOB, and slow DTC, as illustrated in Figure 9 and summarized in the Table 1.

Some previous lithostratigraphic and age assignments to Baluti Formation are controversial. Multiple argillaceous intervals above and beneath the currently designated Baluti Formation have been assigned to "Baluti Shale." However, the key criteria for the formation are the thickest argillaceous rock with highest GR, low RES, low RHOB, and slow DTC. There are other argillaceous rocks with similar log character Upper Triassic-Lower Jurassic interval, but they are much thinner than the Baluti Formation, as demonstrated in Figures 8 and 9.

The thickness of Baluti Formation is 36m in type section and 53m in Sirwan outcrop in SE Kurdistan. In subsurface, it is 34-87m in the north region but increases to 90-140m (all measured depth) towards south Kurdistan. Lithologically, the north sections are sandier and more argillaceous than in the central and south sections (Figure 9).

The palynomorph assemblage from the type section of Baluti Formation was interpreted as Carnian age by Hanna (2007). An identical palynomorph assemblage from the Jebel Kand-1 Well, however, was interpreted as Norian by Al-Kobaysi (2011). Strontium stable isotope age-dating of the upper Kurra Chine Formation anhydrite in Atshan-1 well and its regional equivalents (Mulussa in Syria and some more recently drilled Kurdistan wells) generated Carnian age for the lower part and middle Norian ages for the upper part of Kurra Chine Formation, and the overlying basal Sarki (Butmah) Formation is late Norian (Grabowski and Liu, 2010). These confine the Baluti Formation to the middle-late Norian of the Late Triassic. This is consistent with the palynological study by Al-Ameri (cited by Aqrawi et al., 2010).

Sarki Formation

The Kurdistan Stratigraphy Workshop recommended replacing "Butmah Formation" with "Sarki Formation" because the uppermost Butmah Formation in the type section (Butmah-2 Well) was faulted out (van Bellen et al., 1959), and controversy arose from change in definition by later workers, as summarized by Buday (1980).

The Sarki Formation was established based on an outcrop in north Kurdistan for the predominantly carbonate interval between the top of Baluti Formation and the base of Adaiyah Formation of the Sehkaniyan Group (discussed below). The top of the Sarki Formation should coincide with the base of overlying Adaiyah Formation, which, however, was defined at the base of the third anhydrite bed cluster in its type section in the Adaiyah-1 Well (van Bellen et al., 1959). This lithologic pick can be easily correlated with the north composite in north Kurdistan wells. It becomes more difficult to follow for central and south regions due to increased number of thinner anhydrite beds, especially when RHOB and DTC log curves are missing (Figure 10). In the north composite, the change in GR curve is subtle across the Sarki-Adaiyah contact. A higher RES and intervals of high RHOB reflecting anhydrite beds are observed for the Adaiyah Formation. Trends in log curves can also be applied for stratigraphic correlation of argillaceous-evaporite-carbonate cycles in south and central regions. The log-based pick criteria are graphically illustrated in Figure 10 and summarized in Table 2.

The stratal thickness of the Sarki Formation is relatively uniform. It is 303m in outcrop type section, 397m in north composite and 432m in south composite. The slightly thinner thickness in outcrops is probably partially caused by dissolution of evaporite, and the thicker subsurface section (>538m in Butmah-2 Well) is likely due to dipping beds or section repeat.

The age of the Sarki Formation can be constrained with biostratigraphy and strontium stable isotope ages. The upper Sarki Formation contains Early Jurassic larger benthic foraminifera (*Siphovalvulina colomi*, *Haurania deserti*, *Amijiella amiji*, etc.) and yields Sinemurian strontium age. The Rhaetian (latest Triassic) larger benthic foraminifer species (*Triasina hantkeni*) is consistently found in the massive clean carbonate in the lower Sarki in outcrops and from several exploration wells. The basal part of the lower Sarki contains *Aulotortus* spp. without *Triasina* sp. and yields late Norian strontium age (Grabowski and Liu, 2010). Therefore, the Sarki Formation ranges from the late Norian of Triassic to Sinemurian of the Early Jurassic.

Sehkaniyan Group

The Kurdistan Stratigraphy Workshop agreed to adopt Sehkaniyan (Formation) and elevate it to Sehkaniyan Group to include the Alan-Mus-Adaiyah Formations. The Sehkaniyan Formation was established from an outcrop on Surdash Anticline in Sulaimaniya, NE Kurdistan (van Bellen, et al., 1959), where the formation is 180m of predominantly carbonate, with brecciated dolostone and limestone interpreted as due to dissolution of anhydrite. In subsurface, the equivalent interval is divided into three lithostratigraphic units, Adaiyah, Mus, and Alan formations in ascending order, all based on exploration wells in north Mesopotamian Basin.

The Alan Formation was initially established in the Alan-1 Well for the 55.5m massive evaporite (anhydrite and halite) immediately beneath the Sargelu Formation (van Bellen et al., 1959). However, an unpublished IPC report, dated 1961, extended its base to include an additional 31m of anhydrite and carbonate. The thickness of Alan Formation ranges 70-160m in most Kurdistan wells, with the exception in one well (Well 4) represented by the central composite where a 241m massive anhydrite is observed (Figure 11), which is very likely due to structural thickening. In NW Kurdistan Dohuk and beyond, the evaporite is gradually replaced by carbonate.

The top of Alan Formation is easily picked at the top of massive anhydrite (regardless of the anhydrite interbeds in the lower part of the overlying Sargelu Formation) with very low and clean GR, high RHOB, and fast DTC log curves, as illustrated in Figure 11 and summarized in Table 2. It can be recognized across the entire region although carbonate increasingly replaces evaporite towards NW Kurdistan. The Alan Formation is restricted to the middle-late Toarcian of Early Jurassic by strontium stable isotope age-dating (Grabowski and Liu, 2010). It is separated from the overlying Sargelu Formation by an obvious hiatus of likely Aalenian age.

The type section for the Mus Formation is in the Butmah-2 Well for the 57m limestone beneath the Alan anhydrite (van Bellen et al., 1959). It is a widespread and uniform shallow, open marine peloidal packstone and/or grainstone (23-57m in thickness), often not dolomitized, representing a condensed interval in an overall evaporitic lowstand part of a megasequence. The log characters for the formation include low and clean GR, low RES, low RHOB and fast DTC (Figure 11).

The type section for the Adaiyah Formation is in Adaiyah-1 Well for the 90.5m anhydrite-carbonate section (van Bellen et al., 1959), with the top placed at the anhydrite beneath the Mus carbonate. Its base is at the contact with the underlying Sarki Formation, usually at the base of the third evaporite cluster in north Kurdistan (Figure 11). The RHOB data is missing in both central and south composite sections where anhydrite interbeds become more numerous but thinner; GR and RESS/RESD trends from the Adaiyah-Mus contact and lithology description from cutting samples can be used for recognizing the base Sarki-Adaiyah contact. The stratal thickness of Adaiyah Formation is regionally consistent (68-88m) when known structural thickening is removed.

Sargelu and Naokelekan Formations

The Sargelu and Naokelekan formations both contain world-class source rocks and are potential reservoirs. Therefore, they are separated in some works but lumped together in others, causing confusion in correlation. The top of Naokelekan Formation is consistently picked at the top of the most organic-rich shale with highest GR (Figure 12 and Table 2). The Sargelu-Naokelekan contact is at the base of the most organic-rich shale in the south composite. Nevertheless, the number of thin organic-rich shale beds increases in the central and north composite section. This contact can either be placed at the base of all organic-rich shale (A) or alternatively at the base of the second organic-rich shale (B in Figure 12).

The type section for the Naokelekan Formation in Rowanduz outcrop in northeast Kurdistan is only 14m thick, composed of an organic-rich calcareous shale, a thin "mottle beds of limestone" with ostracods and ammonites, and then an extremely bituminous shaly limestone or organic shale ("coal horizon") with thin shelled pelagic bivalves (*Bositra* spp. or "filaments") in descending order. The thickness of Naokelekan Formation ranges from 14-39m in subsurface in Kurdistan. The thicker Naokelekan Formation is probably due to inclusion of additional organic-rich shale and limestone interbeds, which can be alternatively placed into Sargelu Formation, as scenario A suggests in the north and central composite (Figure 12).

The Sargelu Formation was established in an outcrop in Sulaimaniya District in northeast Kurdistan, where it is 115m thick (van Bellen et al., 1959). The formation is easily recognized as between the "coal beds" of lower Naokelekan and the massive anhydrite of the Alan Formation. The upper part of Sargelu Formation contains abundant thin-shelled bivalves (*Bositra* spp.). Rhynconellid brachiopods, and the Middle Jurassic planktonic foraminifera (*Conoglobigerina* spp.) also occur in cleaner limestone beds deposited in open marine environment.

The Sargelu Formation is a deepening upwards megasequence consisting of marginal to shallow-marine carbonate with anhydrite interbeds in the lower part, a condensed intrashelf basinal organic-rich argillaceous limestone in the middle, and a highstand middle to deep shelfal clean limestone in the upper part. The thickness of the entire unit varies from 79-257m (MD) in subsurface sections. Very commonly, the cleaner limestone accounts for the major part of the increased stratal thickness of the formation (Figure 12). Probably, this is due to higher carbonate productivity and creation of more accommodation in some areas.

The age of Sargelu Formation is Bajocian-Bathonian of Middle Jurassic. The age of Naokelekan Formation has not been well determined, likely from the Callovian to Oxfordian, with possibility of early Kimmeridgian (van Bellen et al., 1959; Aqrawi et al., 2010).

Gotnia Group

Following the rationale for the establishments of Shiranish, Kolosh and Pila Spi groups discussed below, this study proposes to elevate Gotnia (Formation) to group status to include several lithostratigraphic units (Gotnia anhydrite, Barsarin carbonate-anhydrite, and Najmah carbonate) representing different lithofacies of the Upper Jurassic. The contact between Gotnia Group and overlying Chia Gara Formation (shale) varies from continuous to disconformity. In any case, this surface can be consistently picked by an abrupt change from low to high GR, high to low RHOB and fast to slow DTC (Figure 13 and Table 2).

While all workers agree that Barsarin and Gotnia are age-equivalent lithofacies variations, there exist different views regarding the relationships among Gotnia/Barsarin, Najmah and Naokelekan Formations, especially, the correlation of Najmah Formation with other Upper Jurassic formations. The suggested relationship of Najmah Formation with other lithostratigraphic units include: 1) age-equivalent to the entire Naokelekan Formation (van Bellen et al., 1959; Aqrawi et al., 2010); 2) age-equivalent to Naokelekan and lower part of Gotnia/Barsarin in north and west Iraq (van Bellen et al., 1959; Jassim and Buday, 2006a); and 3) age-equivalent to Barsarin and Naokelekan combined (Buday, 1980).

The relationship among these lithostratigraphic units can only be resolved with high-resolution chronostratigraphic age constraints (biostratigraphy and stable isotope age-dating), correlation of closely spaced well sections with high-quality well log curves, and more importantly seismic survey data. These are beyond the scope of this work. Nevertheless, the top of Gotnia Group provides a reliable horizon to embrace all scenarios for regional correlation. The age of the Gotnia anhydrite was determined as from late Kimmeridgian to middle Tithonian from strontium stable isotope (Grabowski and Liu, 2010). As a whole, the Gotnia Group is probably from the Oxfordian to middle Tithonian.

The Gotnia Formation in Kurdistan is the thickest in the north skirt of the Najmah Platform, where its upper part is massive anhydrite and the lower part is sandy to clayey carbonate with anhydrite interbeds. Farther to the northwest, the anhydrite is increasingly replaced with carbonates. In central and southeast Kurdistan, the amount of anhydrite significantly decreases or is entirely replaced with thinly bedded peloidal packstone or grainstone. “Barsarin Formation” is applied to these basin-filling carbonates. Najmah Formation is a shallowing-upward carbonate unit. Its basal part contains thinly laminated silty to argillaceous carbonate with radiolarian beds and thin-shelled pelagic bivalves, representing basin-slope deposition. The middle part contains shelfal limestone with echinoid and occasional planktonic foraminifera. The upper part is upper ramp or open platform limestone containing Late Jurassic, larger benthic foraminifera and green algae. Very rarely, traces of anhydrite are observed in petrographic thin sections in middle to upper part, such as in Well 3. The thickness variation and lithofacies of these three Upper Jurassic formations are illustrated in Figure 13, and pick criteria for the respective units are listed in Table 2.

Chia Gara Formation

The type section for Chia Gara Formation is also in north Kurdistan and it is 21m thick (van Bellen et al., 1959). The base of Chia Gara Formation is consistently picked at the contact between the organic-rich or bituminous shale and the underlying Gotnia Group, being either anhydrite of Gotnia Formation, the thinly bedded peloidal grainstone of Barsarin Formation, or the thick, shallow-marine carbonate of the Najmah Formation (Figure 13). The top of Chia Gara Formation can be easily picked at the base of Garagu Formation in north Kurdistan, where the Garagu Formation (shallow-marine clean limestone with larger benthic foraminifera, small benthic foraminifera and green algae of Valanginian age) is present. It becomes increasingly difficult to correlate the top of Chia Gara Formation where the Garagu shallow-marine, clean limestone changes to Sarmord facies (deep shelf to slope, argillaceous limestone) in central Kurdistan, and then transitions to Balambo basinal facies (pelagic radiolarian ooze and marl) in SE Kurdistan. Nevertheless, the Chia Gara Formation is a more argillaceous unit and contains more detrital components than its overlying formations. High GR, low RES, low RHOB. and slow DTC are log characters when comparing with the underlying Gotnia Group and overlying Qamchuqa Group (Figures 13 and 14 and Table 2). Presence of calpionellids indicating Tithonian-early Valanginian age is additional criterion for Chia Gara Formation. Relationship of Chia Gara with Karimia, "Lower Sarmord" and Makhul formations was well summarized by Buday (1980). It is a complex issue and beyond the scope of this work.

Although it is absent from the Mosul High and vicinity areas due to non-deposition and/or erosion, Chia Gara Formation is widespread in the rest of Kurdistan. Its thickness increases from ~20m in north to over 200m in SE Kurdistan. The basal part of Chia Gara Formation has source-rock potential.

The Chia Gara Formation contains ammonites and calpionellids, in addition to abundant radiolaria. Its stratigraphic range is well defined as from the middle Tithonian to early Valanginian.

Qamchuqa Group

The Lower Cretaceous stratigraphy hierarchy is complex, multiple nomenclature systems, and synonyms exist due to greater facies variation. The interval from the top of Chia Gara Formation to the top of Qamchuqa Group was divided into Karimia (as facies variation of upper Chia Gara), Garagu, Sarmord and Qamchuqa formations in LSI (van Bellen et al., 1959).

The "Qamchuqa Limestone Formation" was established by Wetzel in an unpublished company report in 1950 (van Bellen et al., 1959) based on an outcrop in Qamchuqa, Sulaimaniya in central Kurdistan. It became obsolete because its basal part probably includes the Garagu Formation, and the rest was subdivided into the Middle Sarmord, Lower Qamchuqa, Upper Sarmord and Upper Qamchuqa formations by Chatton and Hart (1960, 1961) followed by revisions by Buday (1980), among others. This study adopts the subdivision of the Lower Cretaceous into the Garagu, Lower Sarmord, Lower Qamchuqa, Upper Sarmord and Upper Qamchuqa formations in ascending order.

In terms of sequence stratigraphy, the Lower Cretaceous contains three shallowing-upward megasequences (Karimia-Garagu, Lower Sarmord–Lower Qamchuqa, and Upper Sarmord–Upper Qamchuqa). The tops of Lower and Upper Qamchuqa Formations are each truncated by a major hiatus, whereas the top of Garagu Formation is stratigraphically continuous. This work focuses on the pick criteria for the tops of Lower and Upper Qamchuqa formations, following the definition of Chatton and Hart (1960) and Buday (1980).

Lower Qamchuqa Formation

Most of Kurdistan operators treat the Lower Qamchuqa Formation as age and facies equivalent to the Shuaiba Formation established from Zaibair-3 Well in South Iraq, which has been widely adopted in the eastern states of the Arabian Gulf. It is a massive shallow-marine carbonate of Aptian age and unconformably overlain by Nahr Umr Formation in the type section (van Bellen et al., 1959). Following this definition, the Lower Qamchuqa (synonymous to Shuaiba) Formation is picked in the north and central composite sections for the massive shallow- to marginal-marine carbonate. Thickness of the Lower Qamchuqa Formation ranges from less than 20m to 149m, mostly 40-80m in north and central Kurdistan. It is absent from Mosul High area and changes facies to Sarmord shelfal-slope limestone facies before transitioning to Balambo basinal facies (radiolarian ooze) farther downdip in SE Kurdistan, where the thin, clean carbonate probably correlates with the Lower Qamchuqa (Figure 14).

The top of Lower Qamchuqa Formation is a major sequence boundary, with a hiatus or correlative surface separating the underlying Lower Qamchuqa from the overlying Upper Sarmord (equivalent to Nahr Umr Formation in south Iraq) or directly from the Upper Qamchuqa Formation where the Upper Sarmord Formation is missing. This surface is usually marked by a basal Upper Sarmord coastal-plain shale or shallow-marine argillaceous-sandy limestone with higher GR, low RES, and low RHOB (Figure 14).

The Shuaiba Formation is Aptian age in central and south Iraq (Aqrawi et al., 2010). The massive, clean limestone in Lower Qamchuqa contains similar larger benthic foraminifera and algal assemblage in several north Kurdistan wells and outcrops, as found in Shuaiba type section (van Bellen et al., 1959).

Upper Qamchuqa Formation

The upper part of the Qamchuqa type section established by Wetzel (1950 in van Bellen et al., 1959) was designated by Chatton and Hart (1960) as Upper Qamchuqa Formation. It has been considered as Albian age and equivalent to the Mauddud Formation in south Iraq (Aqrawi et al., 2010; Jassim and Buday, 2006b). The Upper Qamchuqa Formation is a widespread shallow-marine carbonate in north and central Kurdistan and transitions to Balambo basinal facies (planktonic foraminifer wackestone) in the southeast. A deep shelf-slope facies (Upper Sarmord) belt probably exists between the Qamchuqa facies in the central and northwest and Balambo facies in the southeast. Balambo Formation can be divided into the lower and upper parts by a change from radiolarian to planktonic foraminifera wackestone which took place approximately in the early part of late Albian.

Thickness of the Upper Qamchuqa Formation ranges from 68m to 322m in measured depth, with the majority in 150-220m range. The shallow-marine carbonate of the Upper Qamchuqa Formation commonly became coarse crystalline, saddle dolomite with reservoir quality in north and central Kurdistan. However, “saddle dolomite” should not be used alone as the sole criterion for the Upper Qamchuqa. Formation of saddle dolomite due to hydrothermal activity occurs in multiple carbonate formations throughout the Triassic-Paleogene in Kurdistan.

At the top of Upper Qamchuqa Formation is a hiatus separating it from the overlying fossiliferous deep-shelf carbonate Dokan or Kometan Formation in central and north Kurdistan. Its lower contact is either a hiatus, directly overlying Lower Qamchuqa or older strata, or continuous with the Upper Sarmord Formation. Because of the unconformable upper contact, the log criteria for this pick are a sharp increase in GR, a decrease in RHOB, and slower DTC, as demonstrated in Figure 15 and summarized in Table 3.

The thickness of the Upper Qamchuqa Formation ranges from 150-323m in subsurface for central and north Kurdistan. The youngest age of the Qamchuqa in type section is considered as Albian (van Bellen et al., 1959; Buday, 1980). In Kurdistan wells, most of the Upper Qamchuqa Formation became saddle dolomite, and few identifiable microfossils were recovered. This study does not rule out the possibility that part of the Upper Qamchuqa Formation extends into Cenomanian.

Shiranish Group

From the top of Upper Qamchuqa Formation to the top of Cretaceous, more than 10 lithostratigraphy names occur in literature. They can be grossly lumped into two megasequences, the Campanian-Maastrichtian (Bekhme/Aqra, Shiranish, and Tanjero) and Cenomanian-lower Campanian (upper Balambo, Dokan, Gulneri, Kometan, Mushorah, Mergi, and Gir Bir). Both megasequences probably deserve group status but the current well data are inadequate for the subdivision. The Kurdistan Stratigraphy Workshop decided to pick the top of Shiranish Group and leave the internal subdivision for future work.

Because the top of Shiranish Group coincides with the uppermost Cretaceous, it is easily picked with biostratigraphic analysis for the occurrence of Cretaceous planktonic and larger benthic foraminifera (globotruncanids, heterohelids, siderolitids, orbitoids, etc.) and/or nannofossils. However, log character variation is less consistent across the region due to facies variation from deep-shelf planktonic foraminifera wackestone (Shiranish Formation) to upper ramp or reefal limestone (Bekhme or Aqra Formation) or fine, marine clastics (Tanjero Formation). In addition, facies boundaries are time-transgressive, and log-character change reflects only facies variation. For example, the influx of marine clastics (Tanjero Formation) started in early Maastrichtian in High Zagros area but did not reach the Foothill Zone in north Kurdistan until the early Paleocene. In fact, differences between Tanjero and Kolosh or Shiranish and Aaliji formations are more age than lithology (van Bellen, 1959; Jassim and Buday, 2006c). Nevertheless, the Upper Cretaceous-Paleogene transition is still marked by a subtle GR log shift reflecting reduction in carbonate productivity due to the mass extinction event and relative increase in clay minerals (Figure 16 and Table 3).

The thickness of the Shiranish Group varies significantly, especially in foredeep areas. For example, Tanjero Formation alone in its type section (Sirwan Valley in SE Kurdistan) is over 2000m.

Kolosh Group

The Paleocene-Eocene sediments display greater facies variation due to uplifting of the hinterland in the proto-Zagros to the east and northeast of Kurdistan. As a result, multiple lithostratigraphy units were established to reflect various lithofacies. With the same rationale as for the

Upper Cretaceous, two groups are erected to package the various lithofacies of the Paleocene - lower Eocene (Kolosh Group) and middle-upper Eocene (Pila Spi Group), respectively. The boundary between the two groups is placed at the base of the Gercus Formation, which is a major hiatus and sequence boundary.

Three major facies belts existed during the Paleocene-early Eocene. To the east and northeast was an uplifted hinterland which was shedding sediments off to the southwest and west, forming a prograding shallowing-upward clastic sequence of the Kolosh Formation. To the southwest was the northern Mesopotamian Basin receiving deep shelf to basinal calcareous shale or shaly carbonate of the Aaliji Formation. In between was a patchy shoal-reefal-lagoonal carbonate facies designated as either Khurmala or Sinjar Formation. Khurmala Formation was established in Khurmala Dome (Kirkuk-114 Well) in the NW Kirkuk field (van Bellen et al., 1959), and it interfingers with the upper part of Kolosh Formation. Sinjar Formation was based on an outcrop in Jebel Sinjar area (van Bellen et al., 1959), and it does not directly interfere with the Kolosh Formation. Sinjar and Khurmala are not easily separated, probably synonymous because both are upper Paleocene - lower Eocene age and overlain by Gercus Formation. Khurmala is a preferable name for the late Paleocene - early Eocene shallow-marine carbonate in Kurdistan given its geographic proximity.

The Kolosh Group is a shallowing-upward megasequence from top of Shiranish Group (Top Cretaceous) to the base of Gercus Red Beds Formation. The base of Gercus Formation is a major sequence boundary and hiatus across the Kurdistan, except in the Foothill Zone near the Kirkuk Embayment, where age-equivalent rocks are shallow-marine carbonate (Avanah Formation) or deep-shelf argillaceous limestone (Jaddala Formation). The log characters across the Kolosh-Gercus contact include a sharp decrease in RHOB and a slower DTC, as shown in Figure 17 and summarized in Table 3.

Pila Spi Group

Lithostratigraphy units included in the Pila Spi Group are Gercus, Avanah, Pila Spi, and Jaddala formations representing alluvial-fluvial clastics, upper ramp-shoal to marginal-marine carbonate, and deep-shelf-basinal argillaceous limestone, respectively. The top of Pila Spi Group is a major hiatus, separating the Eocene from various overlying lithostratigraphy units (commonly the Lower Fars) across the Kurdistan, except for the Foothill Zone where the Eocene (Jaddala) to Oligocene (Kirkuk) transition is gradational (van Bellen et al., 1959; Jassim and Buday, 2006d). Pila Spi Formation has widespread surface exposure in Kurdistan and can be of reservoir quality in subsurface. However, it is only of economic significance in Foothill Zone, where it is buried beneath biodegradation zone.

The top of Pila Spi Group is easily picked for its carbonate lithology with contrasting log characters (low and clean GR, fast DTC, and moderate RHOB, Figure 18), where the overlying unit is the Lower Fars Formation (Figure 18 and Table 3). Otherwise, it is readily separated from either the Kirkuk or Euphrates carbonate (for its Eocene age).

Lower Fars (Fatha) Formation

Various lithostratigraphy units overlie the Eocene Pila Spi Group; they include the Kirkuk and Euphrates Groups (up to 13 formations are included in these two groups), but most commonly in Kurdistan is the Lower Fars Formation. Euphrates and Kirkuk groups (*sensu* Buday,

1980) have sporadic occurrence in Kurdistan, and there is limited data for discussing their stratigraphic characterization for this study. This work instead focuses on the Lower Fars Formation.

The Lower Fars Formation was established in SW Iran and adopted by Busk and Mayo in 1918 for the lower-middle Miocene clastics-carbonate-evaporite sequence in Iraq (from van Bellen et al., 1959). Jassim et al. (1984, according to Jassim and Buday, 2006e) established Fatha Formation at Al Fatha Gorge in north-central Iraq to replace the Lower Fars Formation in Iraq. Although Fatha is the more pertinent name, Lower Fars is kept in this study for nomenclature consistency.

The Lower Fars Formation is characterized by thick and multiple cycles of limestone-evaporite-clastics, and it can be further subdivided into Basal Fars Conglomerates, Transition Zone, Salliferous Beds, Seepage Beds and Upper Red Beds, in ascending order. The lower part contains more carbonate and evaporite, and the upper part is dominated by multiple cycles of varicolored silty-sandy mudstone, green silty mudstone, red silt-sandstone, and evaporite. The facies evolution indicates decreasing marine influence.

The Lower Fars Formation can reach over 900m in Kirkuk Embayment, where it is complete (Jassim and Buday, 2006e). However, it is often incomplete in Kurdistan. The upper contact with the Middle-Upper Fars (Injana) Formation is recognized as the youngest evaporite (gypsum or anhydrite) with low GR, high RHOB, and fast DTC. Its lower contact varies from a hiatus with various underlying lithostratigraphy units or (dis)continuous with Jeribe Formation. In any case, the basal part of Lower Fars has the log characters of serrated GR, RES, RHOB, and DTC, reflecting multiple carbonate-clastic-shale-evaporite cycles, as illustrated in Figure 19 and summarized in Table 3.

The stratigraphic range of Lower Fars Formation has been equivocal, as summarized by Aqrawi et al. (2010). Van Bellen et al. (1959) did not provide direct evidence for age assignment. They nevertheless placed it in the middle Miocene, likely based on its stratigraphic contexts. According to Buday (1980), Ponikarov et al. (1967) assigned the formation occurring in Syria to “Middle Miocene Tortonian,” while Tortonian is the oldest stage of upper Miocene in current standard timescale.

Aqrawi et al. (2010) adopted a late Burdigallan-early Serravallian age from the strontium stable isotope age analysis of Lower Fars in Iran by Ehrenberg et al. (2007). Strontium stable isotope analysis of anhydrites and limestone from various members of the Lower Fars Formation by Grabowski and Liu (2009, 2010) provide direct age constraints for the units at various localities in Iraq: the age of Transition Beds is early to middle Burdigalian, the Salliferous Beds is middle to late Burdigalian, the Seepage Beds is latest Burdigalian, and the Upper Red Beds is late Burdigalian to middle Langhian. Considering that the youngest Lower Fars usually does not have adequate material (uncontaminated anhydrite or gypsum) for strontium analysis, it is possible that the Lower Fars Formation can be as young as late Langhian or even early Serravallian. However, its majority is middle Burdigalian to Langhian. This age assignment is similar to the summary by Aqrawi et al. (2010).

Summary/Conclusion

With well log and lithology data from recently drilled wells the MNR provided, three subsurface composite lithostratigraphy reference sections for the north, central, and south Kurdistan are established for regional correlation. Representatives from the MNR and major operators in Kurdistan have built consensus on log-based pick criteria for 14 key stratigraphic surfaces for regional correlation and internal calibration. In addition, clarification and minor revision were made for some major lithostratigraphy surfaces to reduce stratigraphic inconsistency for current and future operators.

The Paleozoic penetration is limited to the north Kurdistan. Judging from the similarity between the Paleozoic, especially the Permian, in north Kurdistan and the rest of eastern Arabian Plate, it is very likely that the Paleozoic in the north composite is representative across the region. The Triassic to Middle Jurassic is more or less regionally homogeneous and all major surfaces can be consistently correlated with log curves. The only exception is the Pliensbachian-Toarcian of the Lower Jurassic in NW Kurdistan where carbonate rather than evaporite facies dominates.

Greater lithofacies variation since the Late Jurassic has frequently led to establishment of multiple age-equivalent lithostratigraphy units, causing inconvenience for correlation. Several lithostratigraphic units are grouped and elevated to group status to embrace a sequence-chronostratigraphic packaging to reduce nomenclature redundancy.

Pick criteria for 14 key stratigraphic surfaces are concisely summarized and graphically illustrated with the three reference sections composed from 10 wells. These key surfaces are major sequence boundaries and can serve as anchor points for calibration and correlation at subregional scale. Flexibility for subdividing megasequences into subordinate units to meet specific needs/purpose is left for individual operators.

While conducting this work and from discussions with stratigraphers from government agency and Kurdistan operators, it becomes clear that future study on Kurdistan subsurface stratigraphy should focus on clear and unified designation of fundamental lithostratigraphy units (i.e., formations), their log characters, high-resolution chronostratigraphic constraints, and facies variation. More importantly, data from various disciplines, especially seismic survey data, should be integrated and calibrated. This will lead to a deeper understanding of facies relationship, sequence stratigraphic packaging, reservoir quality and distribution, and ultimately the establishment of refined unified regional and sub-regional stratigraphic framework(s).

Acknowledgements

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References Cited[+]

Al-Kobaysi YHK, 2011, Palynostratigraphy of Late Triassic-Early Jurassic strat in boreholes Tel-Hajar-1 and Kand-1, northern Iraq: Unpublished Ph.D. Thesis, University of Mosul, Iraq, 213p.

Aqrawi, A.A.M., A.H. Al-Hadidy, A.D. Horbury, and F.N. Sadooni, 2010, The Petroleum Geology of Iraq: Scientific Press, 423p.

Aqrawi, A.A.M., A.H. Al-Hadidy, and A.D. Horbury, 2013, Hydrocarbon potential of the Upper Permian Chia Zairi Formation in Iraq, *in* M. C. Pöppelreiter, editor, Permo-Triassic Sequence of the Arabian Plate (Chapter 9): EAGE Publication, p. 77-127.

Buday, T., 1980, Stratigraphy and Paleogeography. Publications of GEOSURV, in I.I.M. Kassab and S.Z. Jassim, editors, The Regional Geology of Iraq, v.1: Baghdad, 445p.

Chatton, M., and E. Hart, 1960, Review of the Tithonian to Albian stratigraphy in Iraq: Unpublished reports of the Iraq Petroleum Company Ltd, Palaeontological Department, Kirkuk, IPR/1, 65p.

Chatton, M., and E. Hart, 1961, Review of the Cenomanian to Maastrichtian stratigraphy in Iraq: Unpublished reports of the Iraq Petroleum Company Ltd, Palaeontological Department, Kirkuk, IPR/2.

Ehrenberg, S.N., J.M. McArthur, N.A.H. Picard, G.V. Laursen, S. Monibi, Z.K. Mossadegh, T.A. Svånå, A.A.M. Aqrawi, and M.F. Thirlwall, 2007. Strontium isotope stratigraphy of the Asmari Formation (Oligocene-Lower Miocene), Southwest Iran: Journal of Petroleum Geology, v. 48/4, p. 727-739.

Grabowski, G. J., and C. Liu, 2009, Ages of Cenozoic strata of NE Iraq (abstract): AAPG Search and Discovery Article 90090 (2009). Website accessed February 7, 2017, http://www.searchanddiscovery.com/abstracts/html/2009/annual/abstracts/grabowski.htm.

Grabowski, G. J. and Liu C., 2010. Strontium-isotope age dating and correlation of Phanezoic anhydrite and unfossiliferous limestones of Arabia (abstract): AAPG Search and Discovery Article #90105 (2010). Website accessed February 7, 2017, http://www.searchanddiscovery.com/abstracts/html/2010/geo_bahrain/abstracts/Grabowski2.html.

Hanna, M.T., 2007, Palynology of the upper part of the Baluti Formation (Upper Triassic) and the nature of its contact with the Sarki Formation at Amadiya district, northern Iraq: Ph.D. Thesis, University of Mosul, Iraq, 219p.

Jassim, S.Z., and T. Buday, 2006a, Late Toracian-Early Tithonian (Mid-Late Jurassic) Megasequence AP7. *in* S.Z. Jassim and J.C. Goff, editors, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, p.117-123.

Jassim, S.Z., and T. Buday, 2006b, Late Tithonian-Early Turonian Megasequence AP8. *in* S.Z. Jassim and J.C. Goff, editors, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, p.124-140.

Jassim, S.Z., and T. Buday, 2006c, Late Turonian-Danian Megasequence AP9. *in* S.Z. Jassim and J.C. Goff, editors, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, p.141-154.

Jassim, S.Z., and T. Buday, 2006d, Middle Paleocene-Eocene Megasequence AP10. *in* S.Z. Jassim and J.C. Goff, editors, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, pp.155-168.

Jassim, S.Z. and T. Buday, 2006e, Latest Eocene-Recent Megasequence AP11. *in* S.Z. Jassim and J.C. Goff, editors, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, pp.169-184.

Jassim, S.Z., and J.C. Goff, editors, 2006, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, 486p.

Jassim, S.Z., T. Buday, I. Cicha, and V. Prouza, 2006, Late Permian-Liassic Megasequence AP6, *in* S.Z.   ehren and J.C. Goff, editors, Geology of Iraq: Dolin, Prague and Moravian Museum, Brno, Czech Republic, p.104-116.

Mackertich, D., and A.L. Samarri, 2014, A decade of exploration in the Kurdistan Region of Iraq: AAPG Search and Discovery Article #30383 (2014). Website accessed February 7, 2017, http://www.searchanddiscovery.com/documents/2014/30383mackertich/ndx_mackertich.pdf.

Ponikarov, V.P., et al., 1967, The Geology of Syria. Explanatory notes on the geological map of Syria. Part 1: Stratigraphy, Igneous Rocks and Tectonics: Ministry of Geology, Russia.

Van Bellen, R.C., H.V. Dunnington, R. Wetzel, and D.M. Morton, 1959, Lexique Stratigraphique International: 03 10 Asie (Iraq), entre National de la Recherche Scientifique, Paris (Reprinted by GulfpetroLink, 2005).

[+]*Many of the lithostratigraphic units summarized in the LSI (van Bellen et al., 1959) were first established by TPC/IPC geologists and documented in internal company reports long before the publication of LSI in 1959. However, most of these reports cannot be publicly accessed because they were "unpublished company reports." Discussion of these lithostratigraphy units is mostly referenced through the LSI. Therefore, the original authors are not credited in this study. Interested readers should refer to the LSI for the vintage of these lithostratigraphy units.1967*

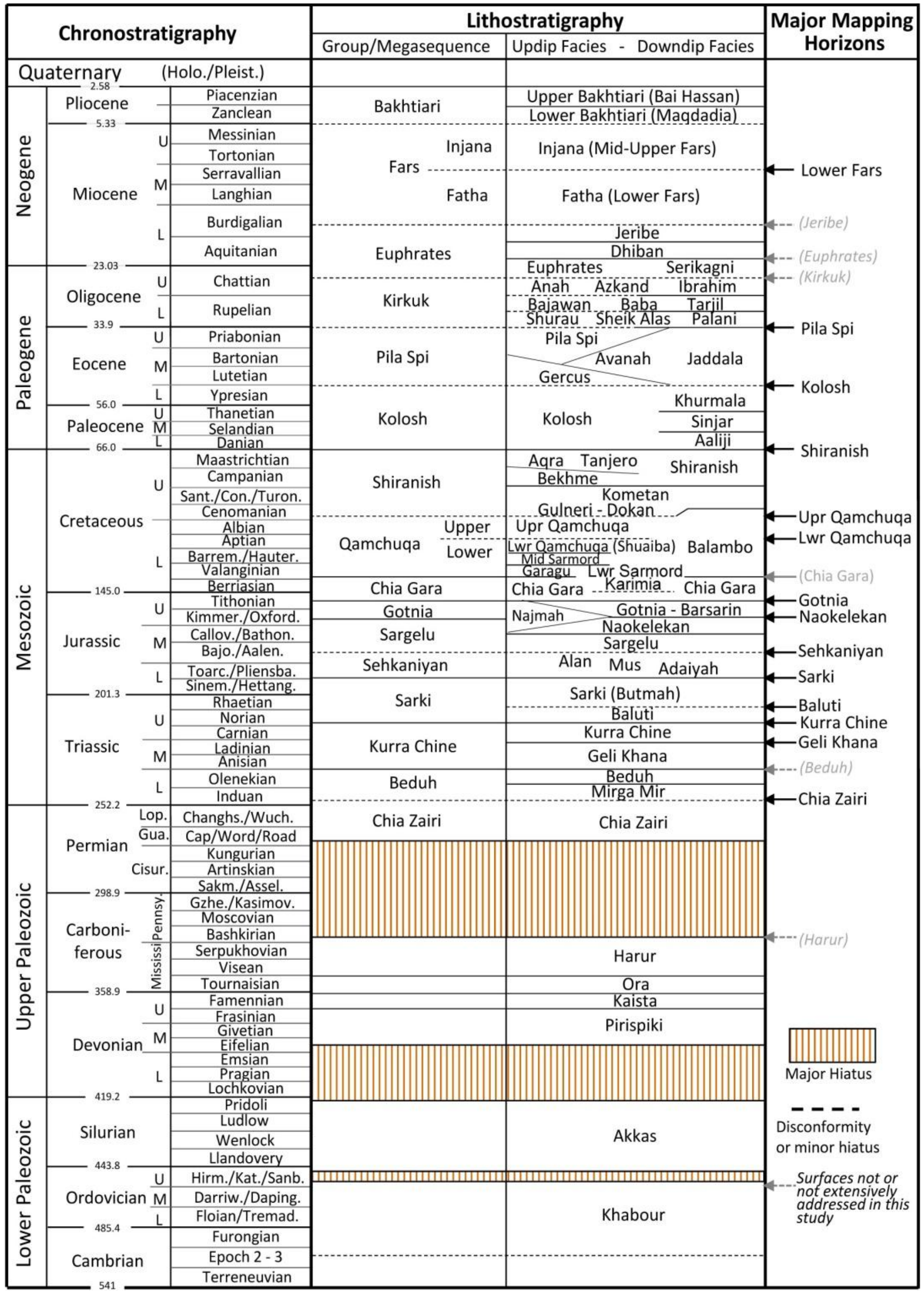


Figure 1. Stratigraphy framework, megasequences, and major mapping horizons for the Kurdistan Region of Iraq.

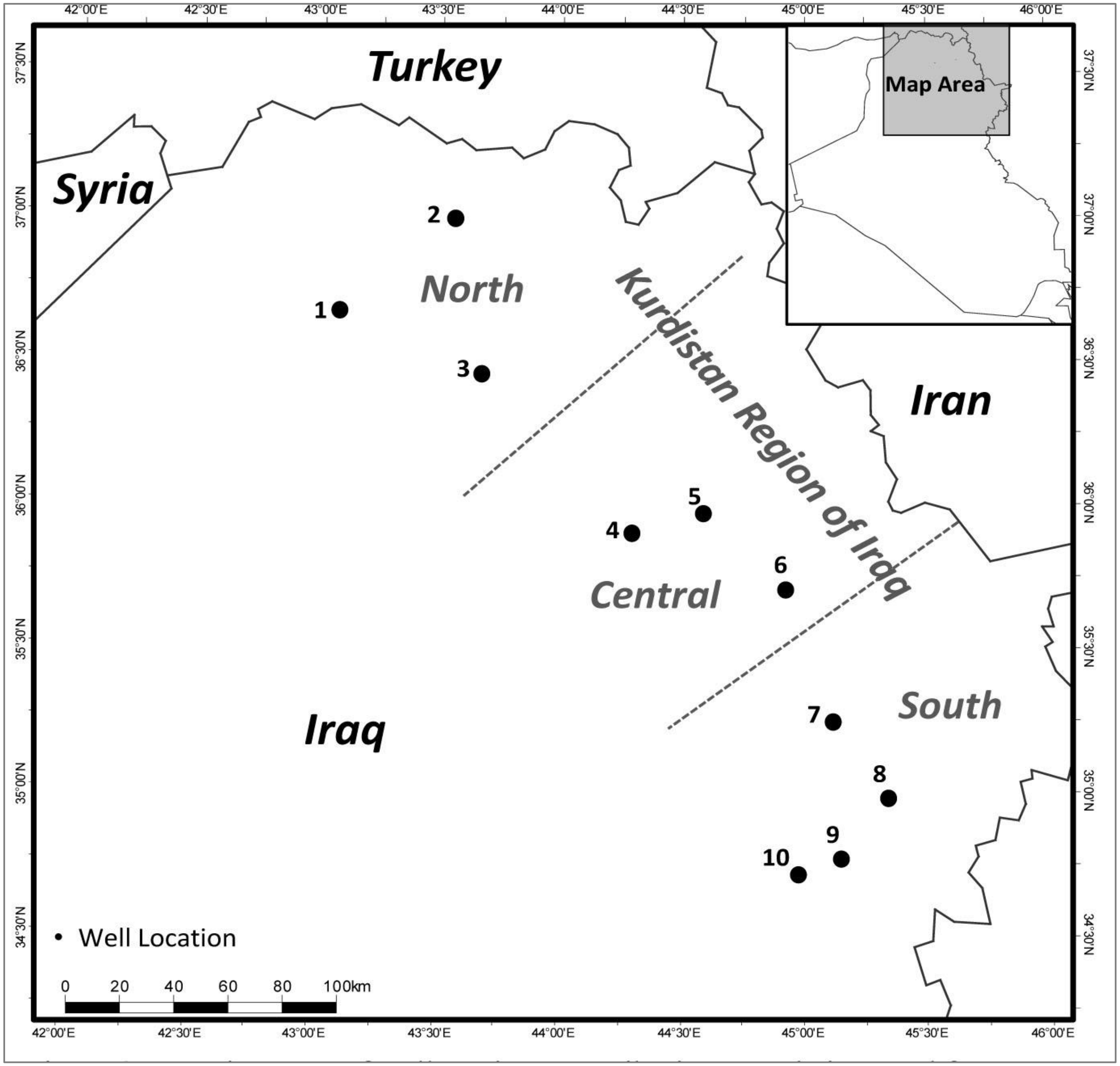
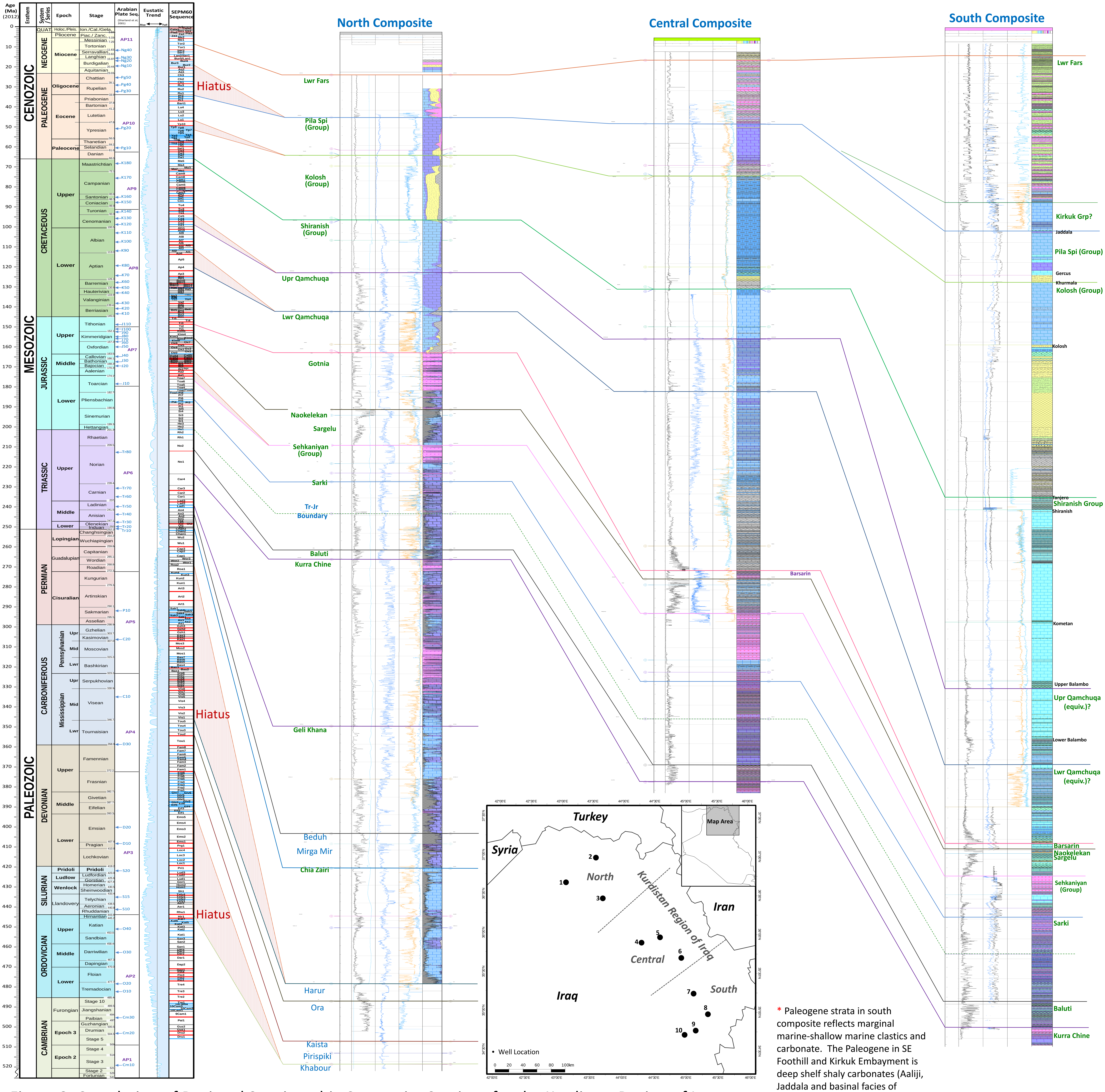


Figure 2. Location map of well sections contributing to or being used for generating the three composite sections.



* Paleogene strata in south composite reflects marginal marine-shallow marine clastics and carbonate. The Paleogene in SE Foothill and Kirkuk Embayment is deep shelf shaly carbonates (Aaliji, Jaddala and basinal facies of Kirkuk)

Figure 3. Correlation of Regional Stratigraphic Composite Sections for the Kurdistan Region of Iraq

Figure 4. Examples of inconsistent stratigraphy framework and nomenclature extracted from stratigraphy reports of various operators. Note that any column is a combination of stratigraphy units picked by several operators.

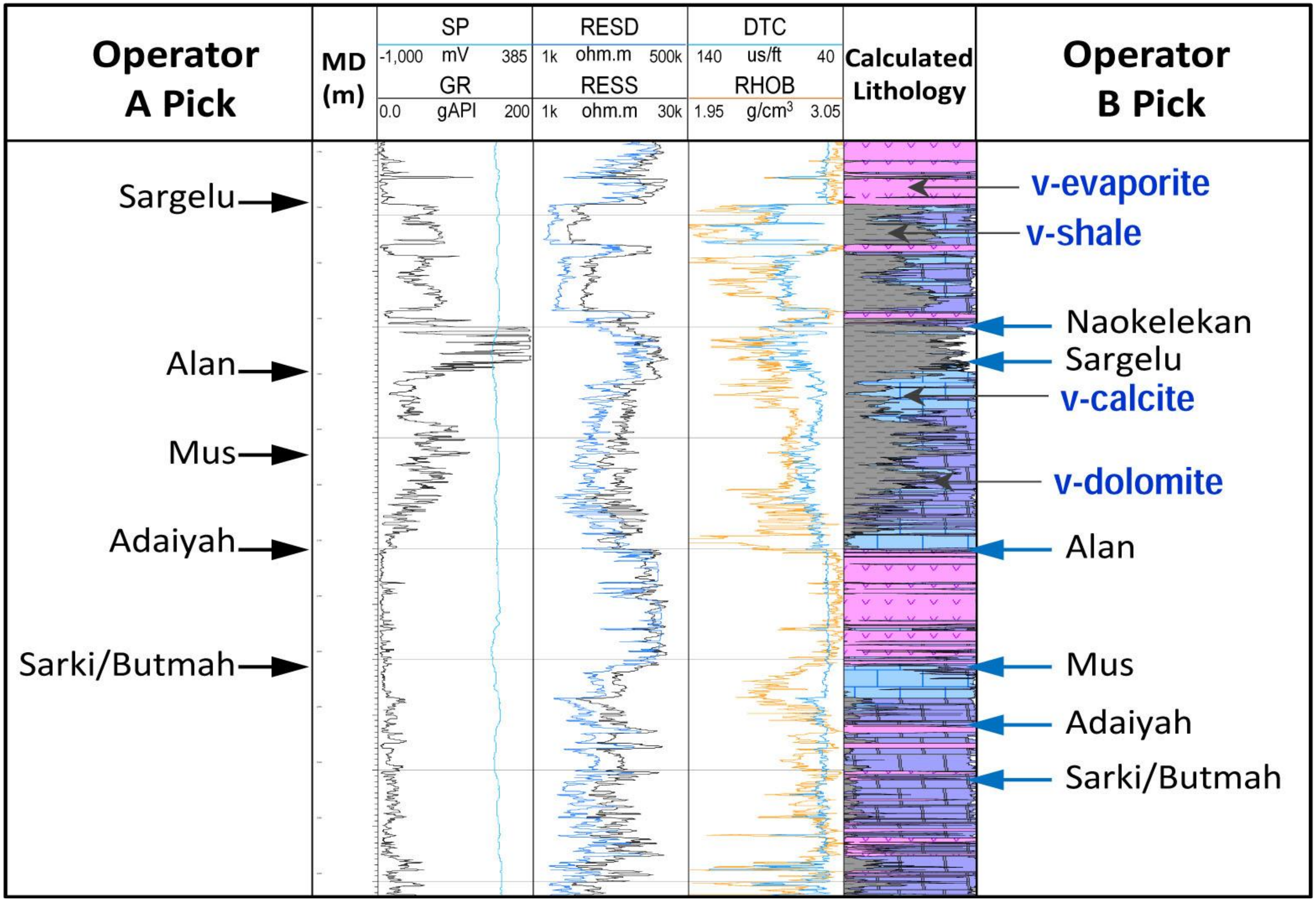


Figure 5. Real example of two competing stratigraphy framework and nomenclature applied to the Lower-Middle Jurassic interval in Well 1, extracted from stratigraphy reports of various operators.

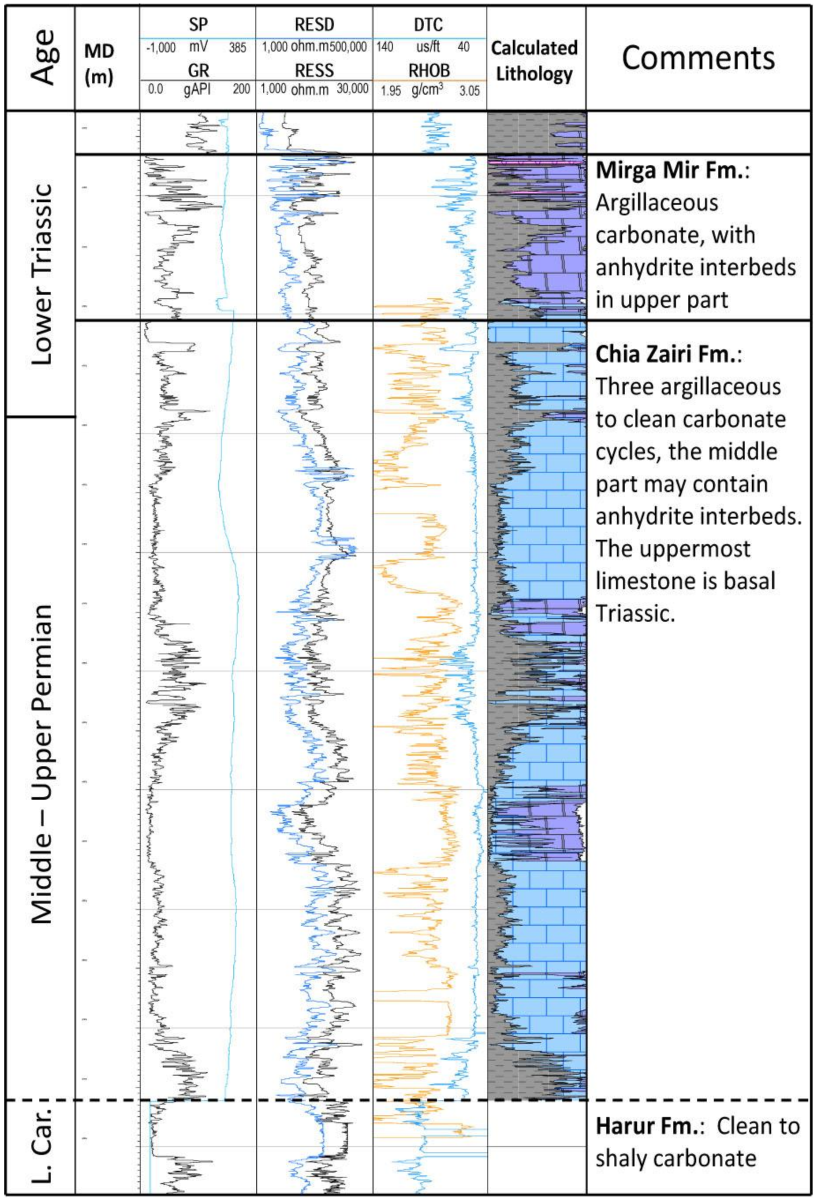


Figure 6. Lithology and log characters of Chia Zairi Formation in the reference section for the north Kurdistan Region of Iraq.

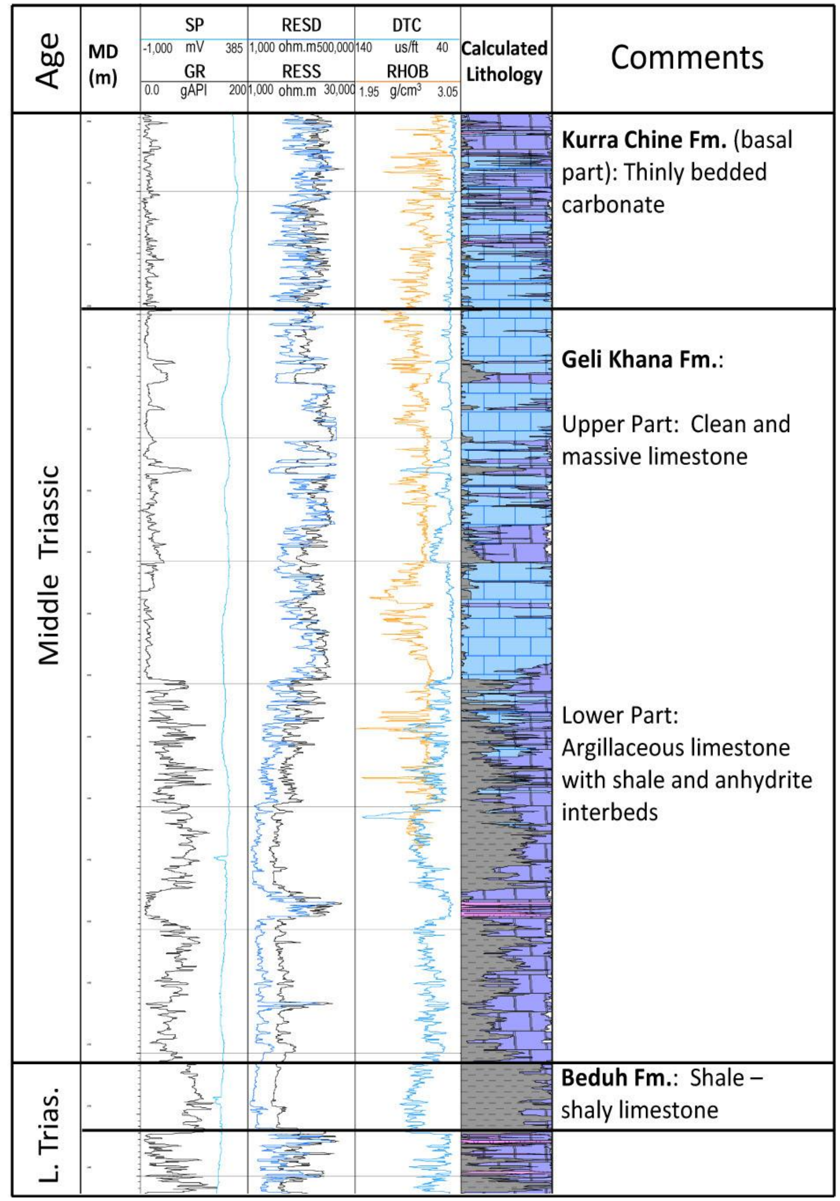


Figure 7. Lithology and log characters of Geli Khana Formation in the reference section for the north Kurdistan Region of Iraq.

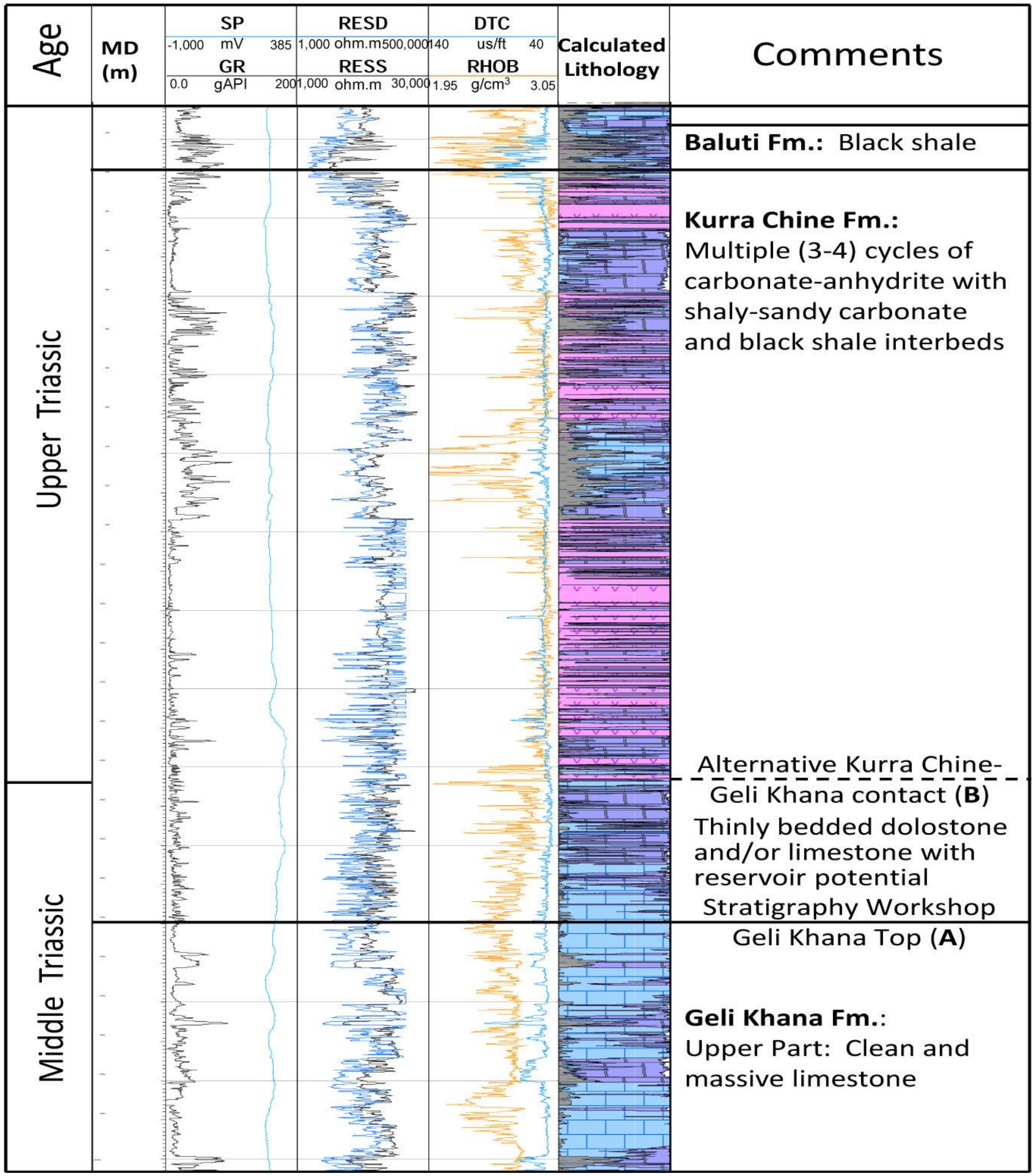


Figure 8. Lithology and log characters of Kurra Chine Formation in reference section for the north Kurdistan Region of Iraq.

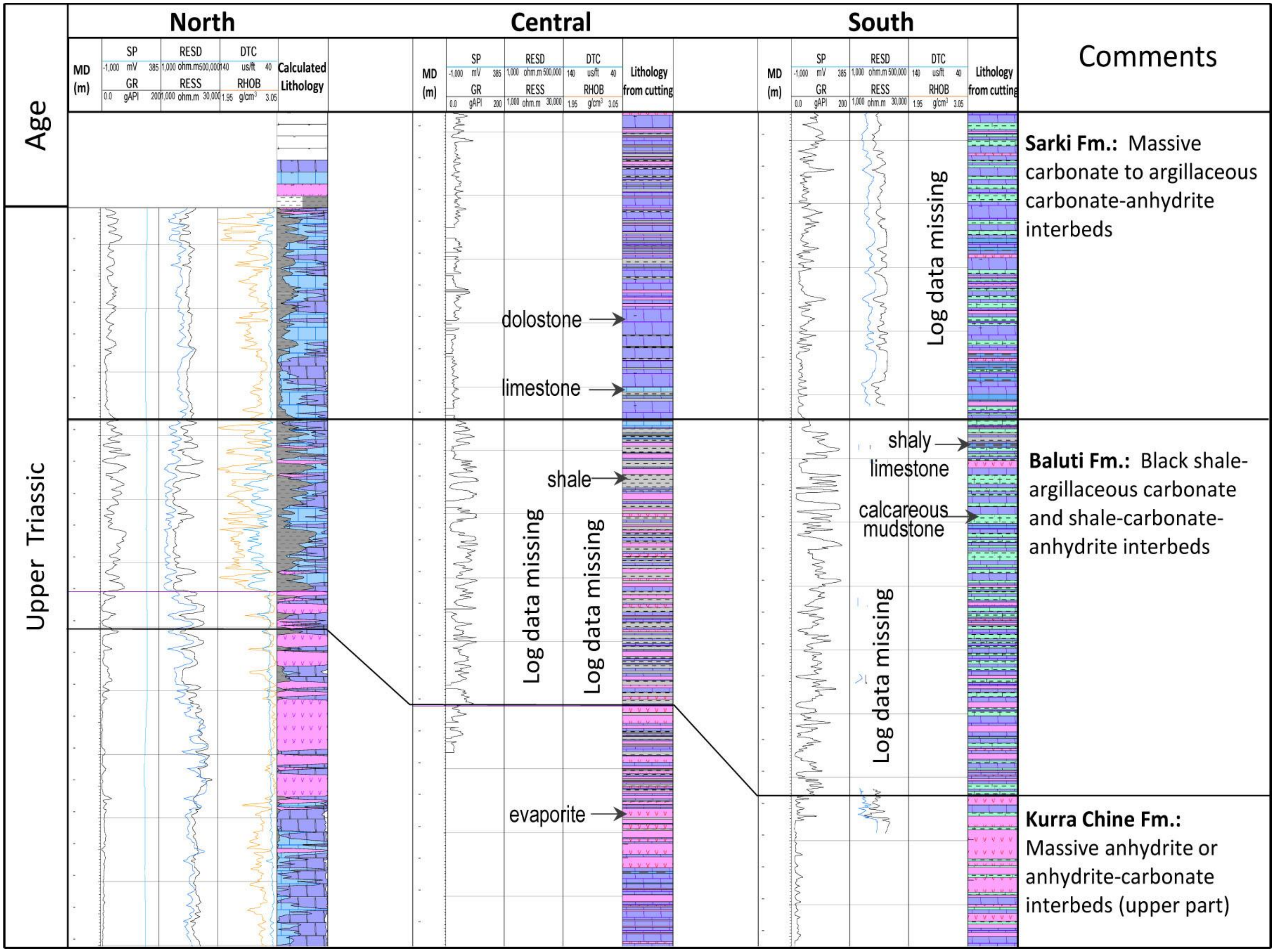


Figure 9. Lithologic and log characters, stratal thickness, and lithofacies variation of Baluti Formation across Kurdistan.

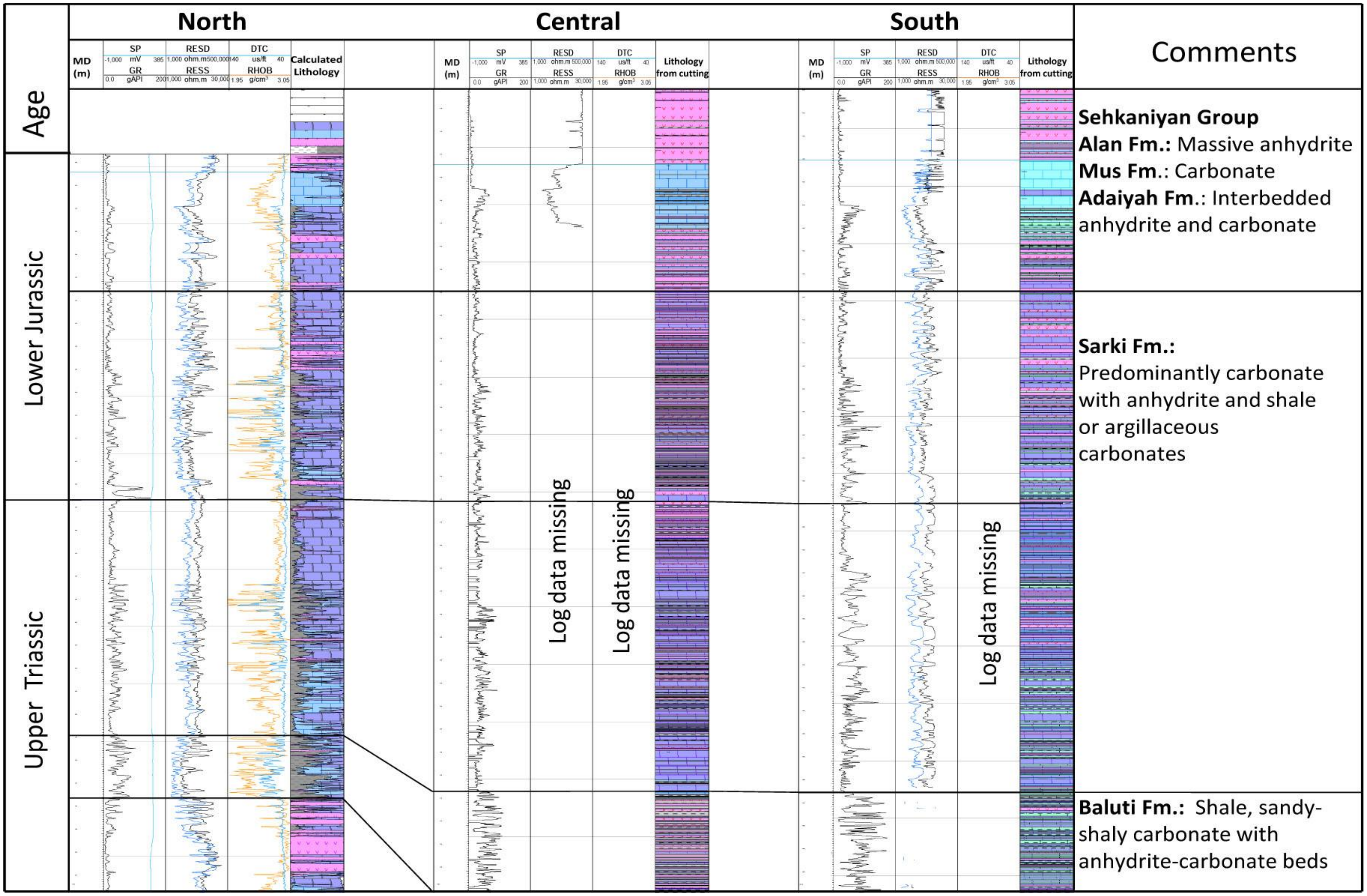


Figure 10. Lithologic and log characters and stratal thickness variation of Sarki Formation across Kurdistan.

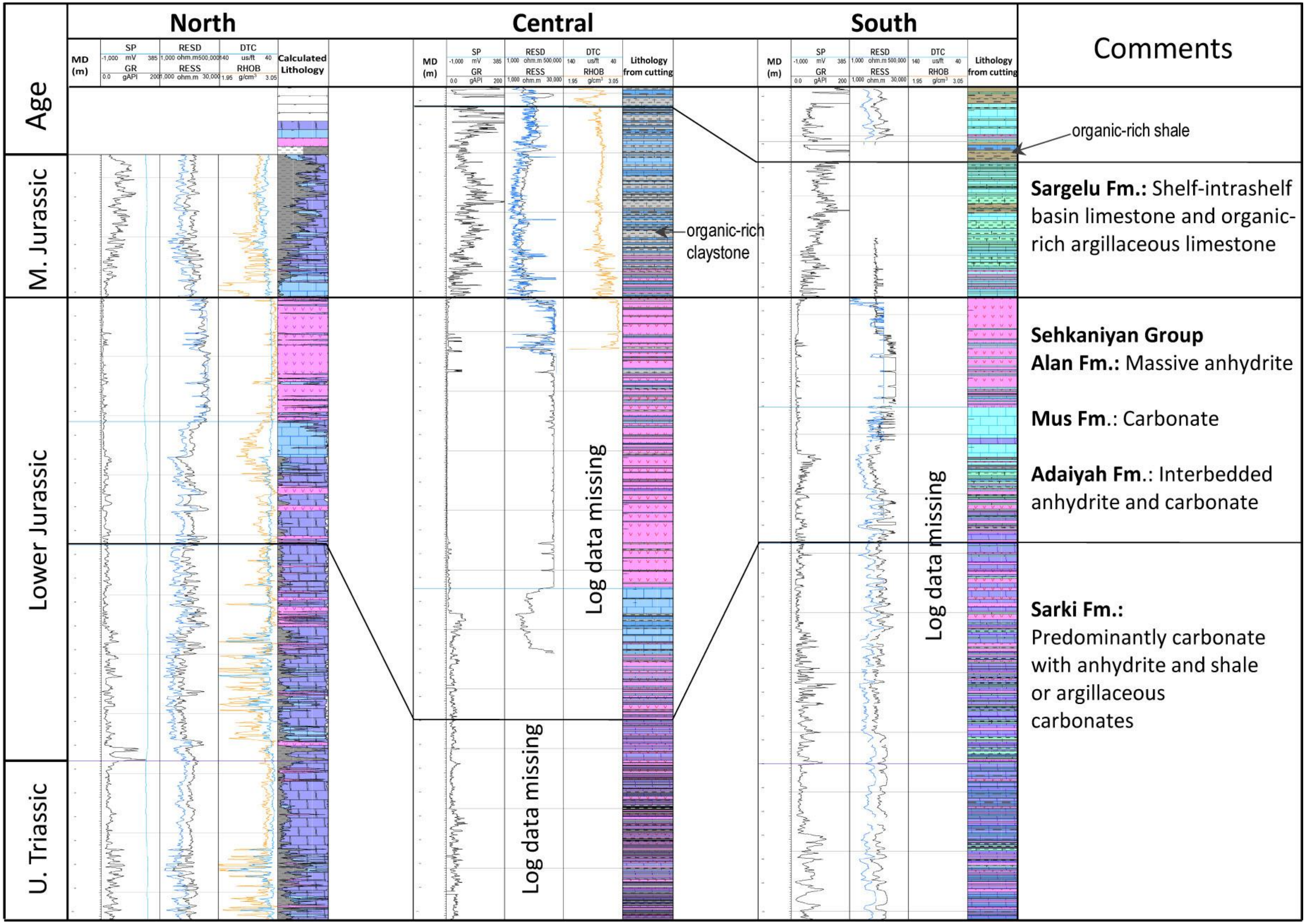


Figure 11. Lithology and log characters and stratal thickness variation of Sehkaniyan Formation across Kurdistan. Note that the thick anhydrite of Alan Formation in central section is measured depth not adjusted for possible structural thickening.

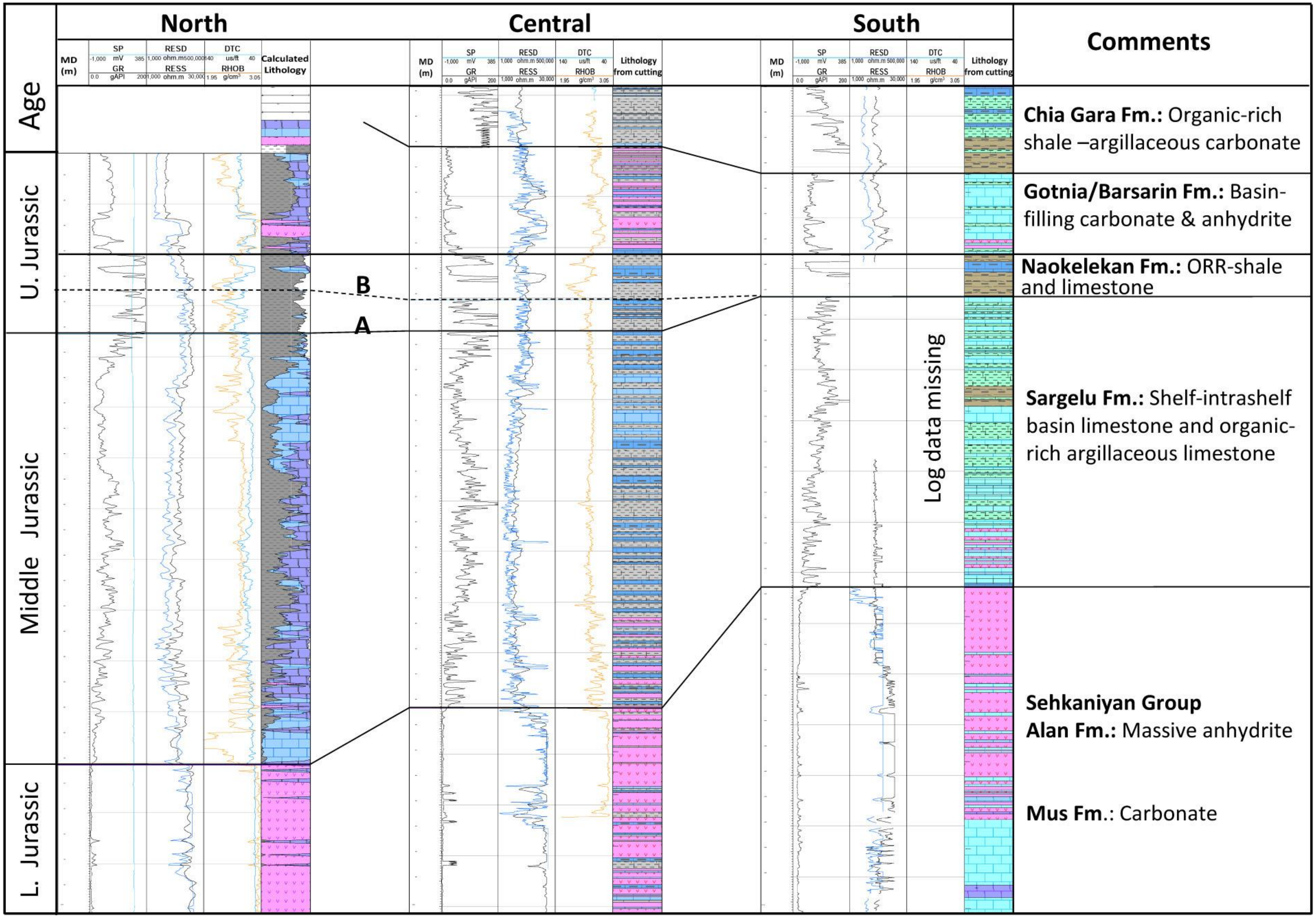


Figure 12. Lithologic and log characters and stratal thickness variation of Naokelekan and Sargelu formations across Kurdistan. Note alternative pick for the Sargelu-Naokelekan contact in the north and central composite sections.

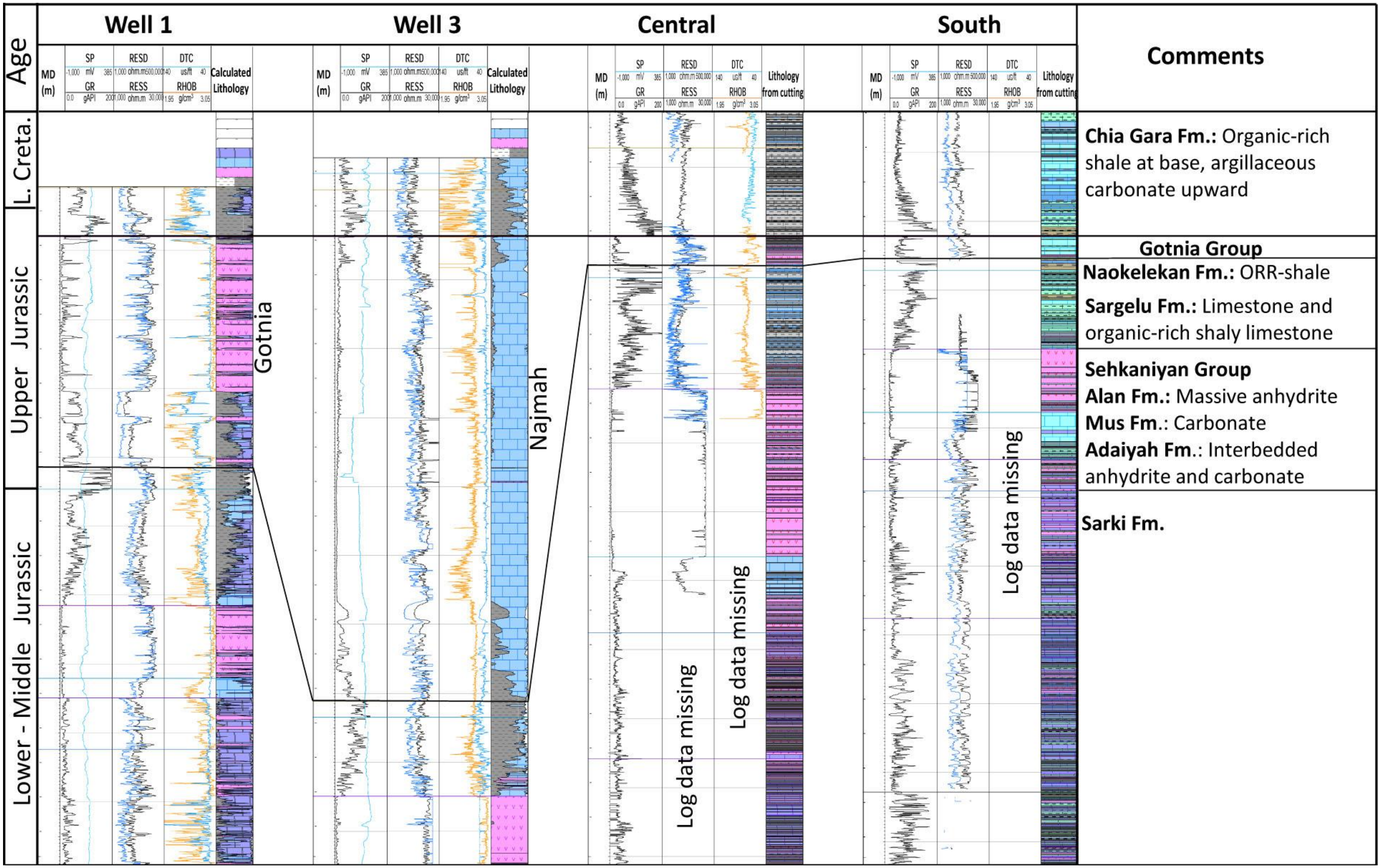


Figure 13. Lithologic and log characters, stratal thickness, and lithofacies variation of the Gotnia Group across Kurdistan.

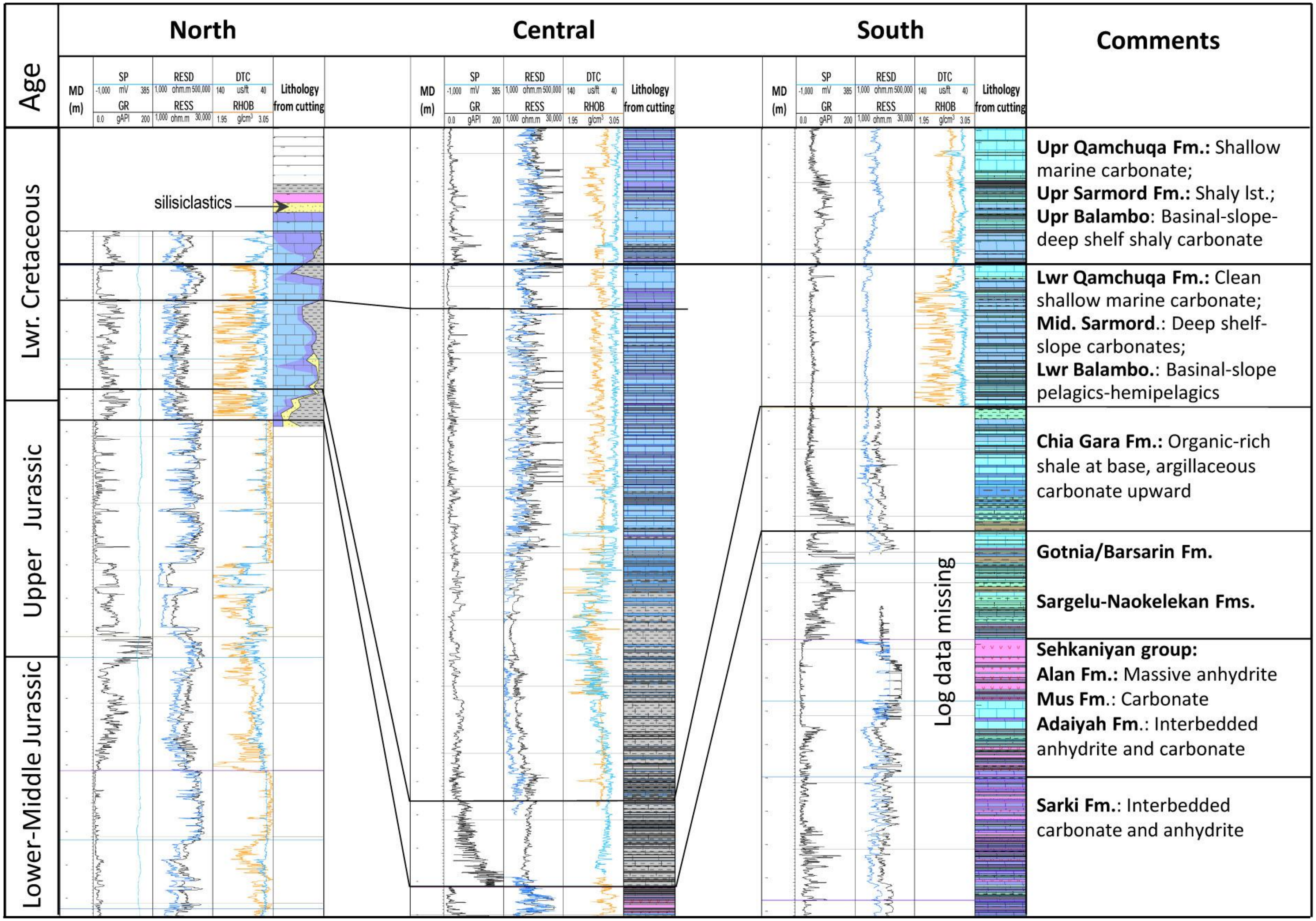


Figure 14 Lithologic and log characters and stratal thickness variation of Lower Qamchuqa Formation across Kurdistan.

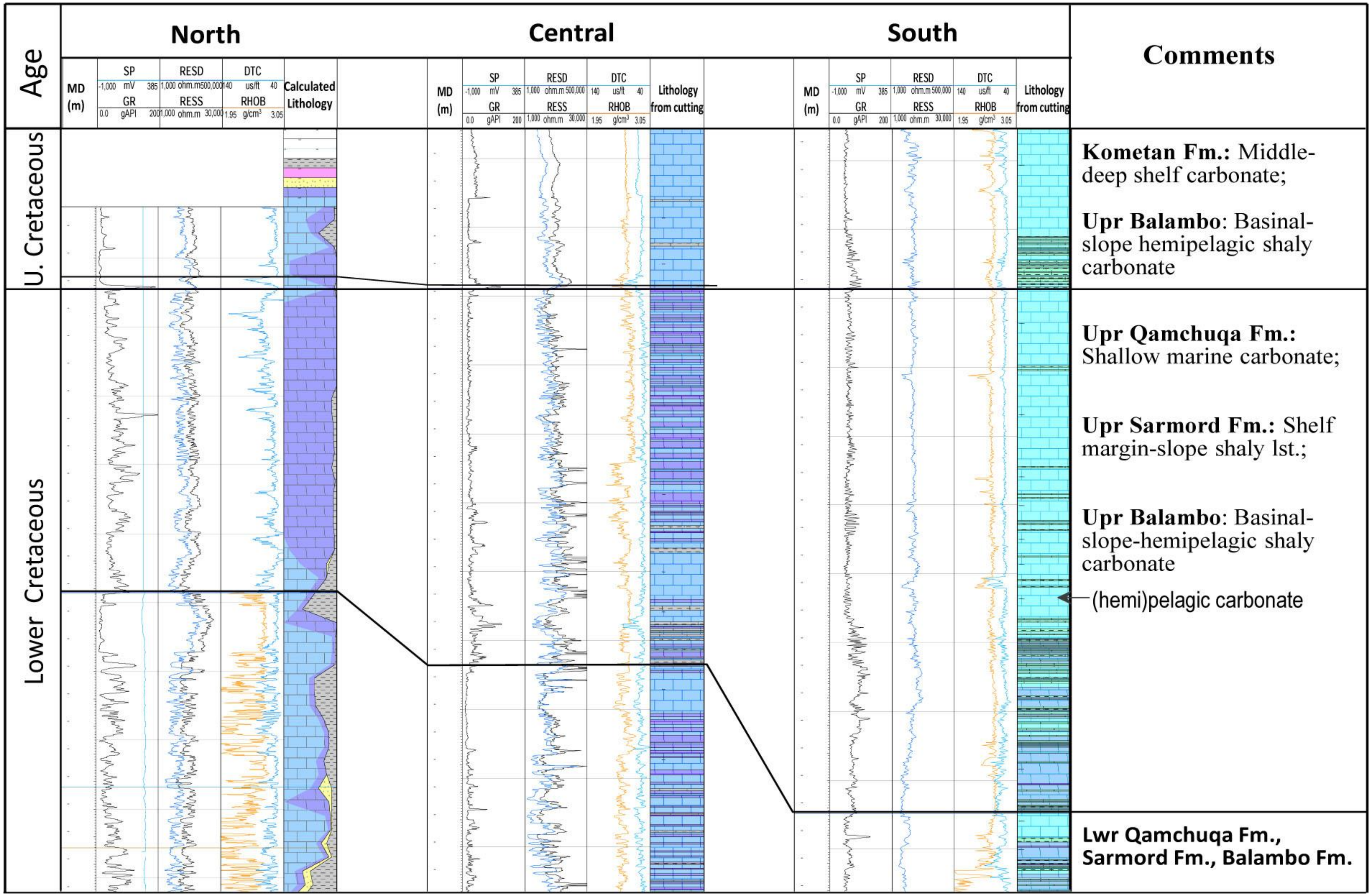


Figure 15. Lithology, log characters, and facies variation of Upper Qamchuqa Formation in north and central Kurdistan. In South Kurdistan, the age equivalent becomes basinal, pelagic-hemipelagic Balambo facies, and interregional correlation becomes less confident.

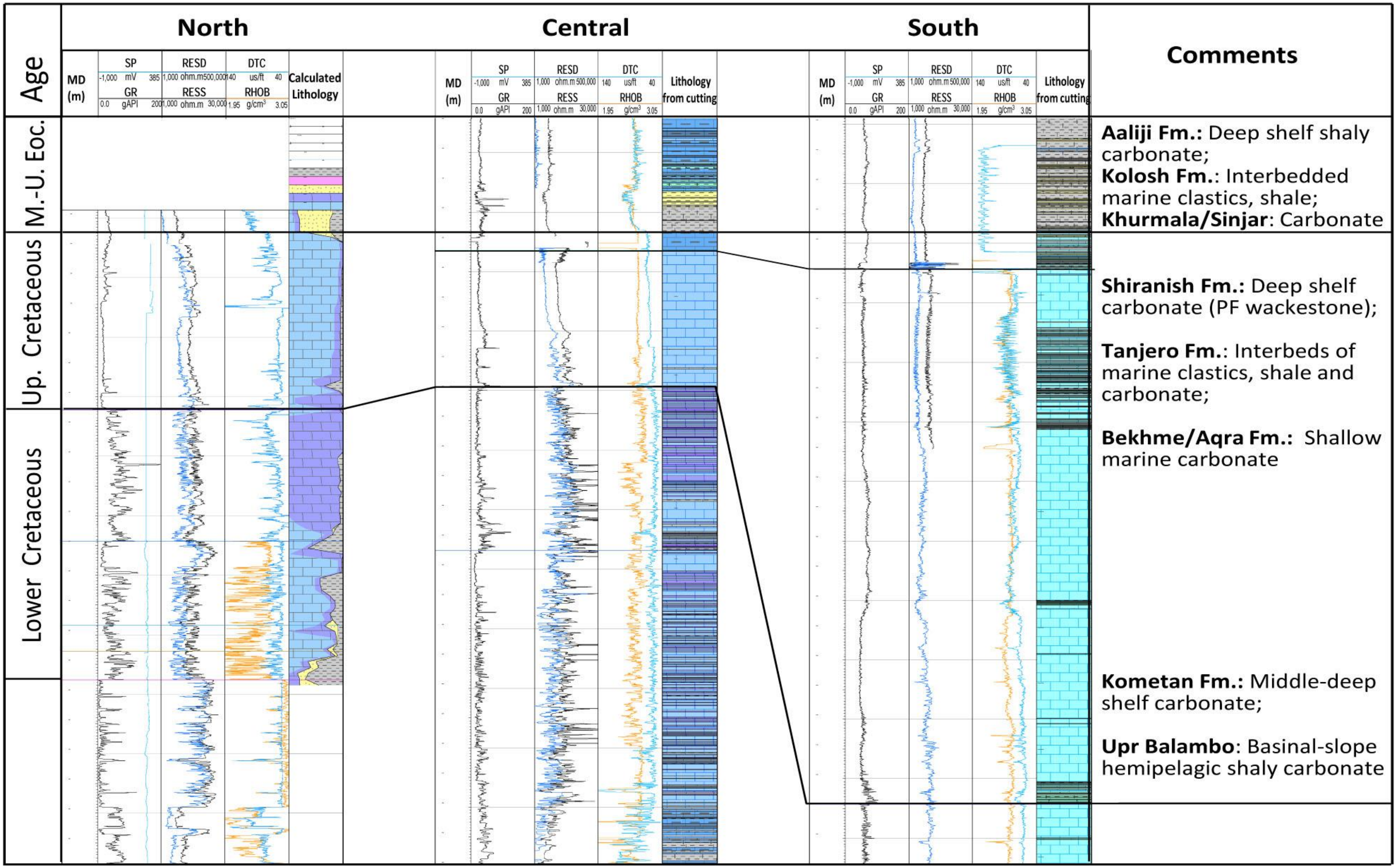


Figure 16. Lithologic and log characters and stratal thickness variation of Shiranish Group across Kurdistan. Note that Tanjero clastics are present in south and central section but missing from the north.

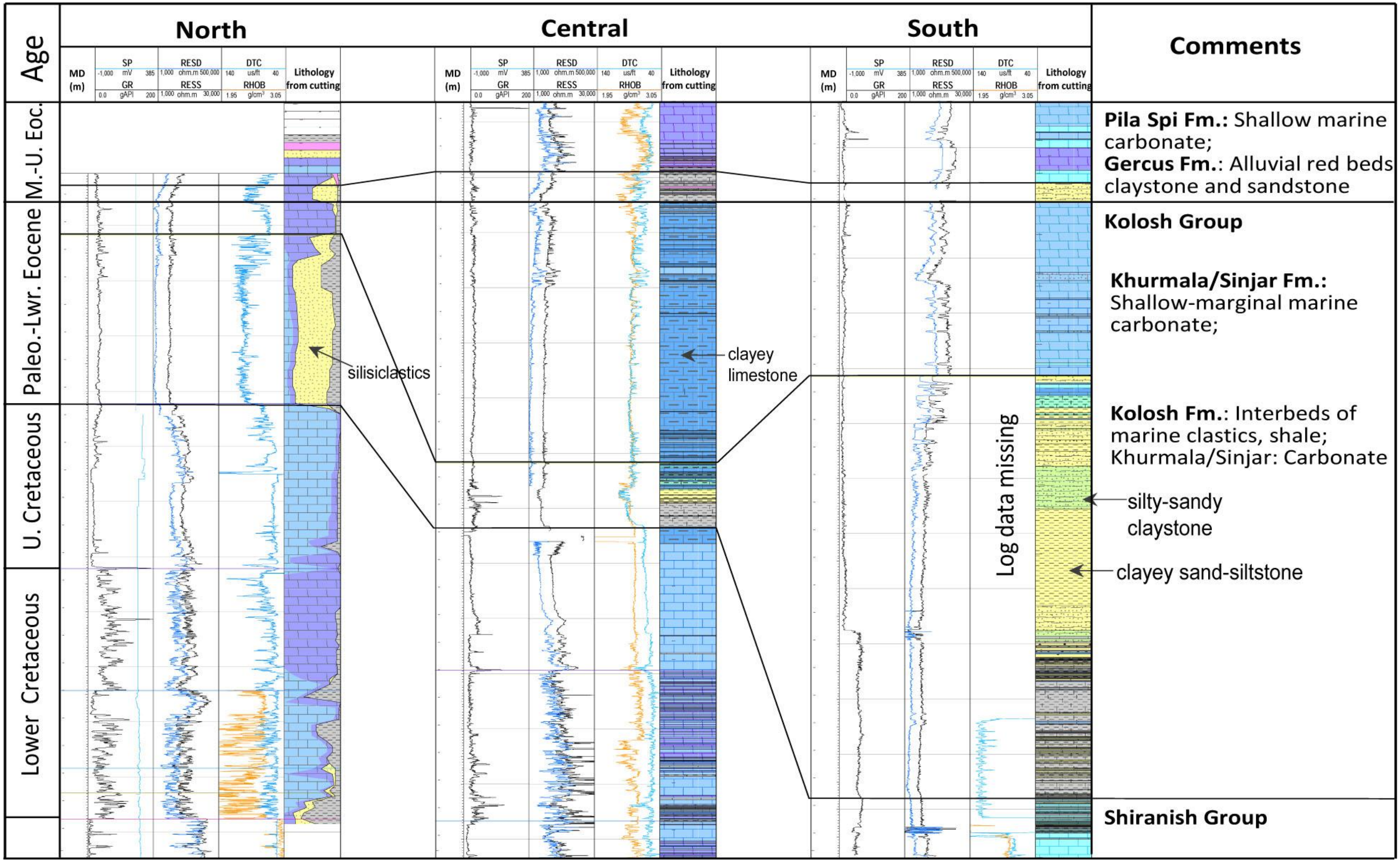


Figure 17. Lithologic and log characters, facies relationship of various lithostratigraphy units of the Kolosh Group, and contact relationship with underlying and overlying units.

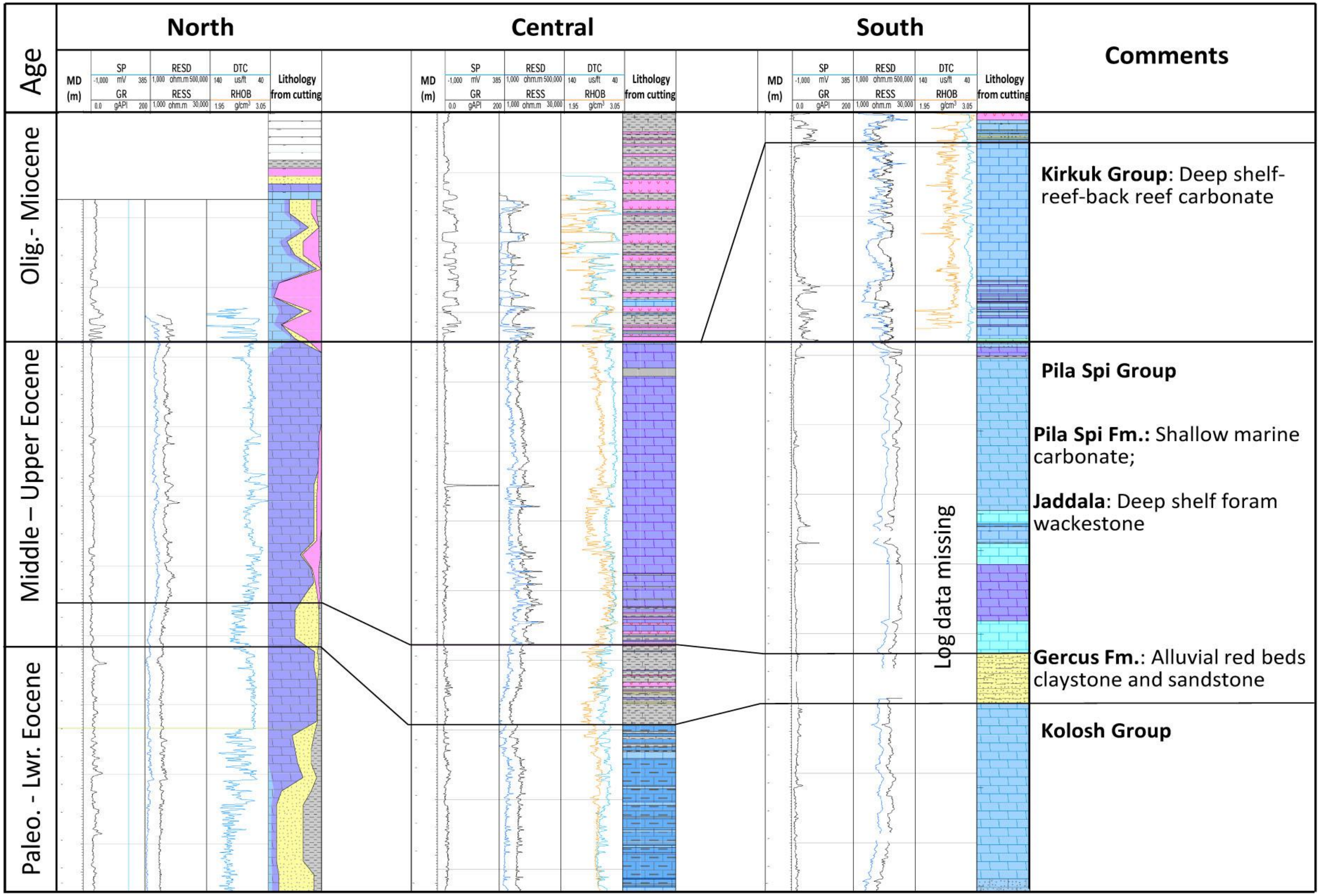


Figure 18. Lithologic and log characters, facies variation of the Pila Spi Group, and relationship with the underlying and overlying units. Note that deep-shelf carbonate of the Jaddala Formation replaced Pila Spi shallow-marine carbonate in southeast Foothill Zone.

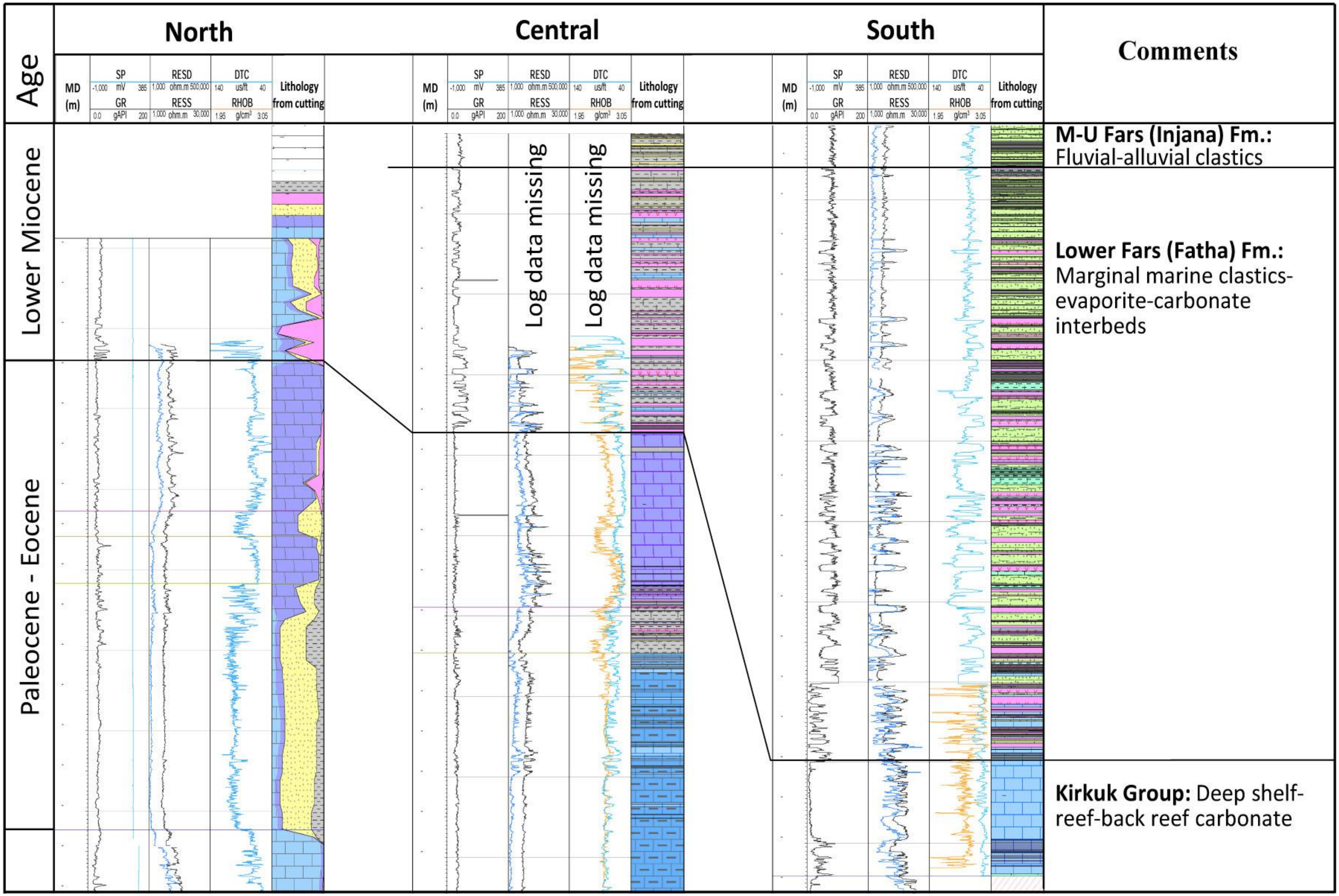


Figure 19. Lithologic and log characters of the Lower Fars Formation; note that the south composite is more complete than the central and north composites, and different underlying stratigraphy units across Kurdistan.

Stratigraphic Surface	Overlying / Underlying Rock	Lithology	GR (Gamma-Ray)	RES (Resistivity)	RHOB (Density)	DTC (Sonic) (comp. wave travel time us/ft)
Baluti Top	basal Sarki	Massive carbonate, often oolitic grainstone	Very low and clean	Moderate	Moderate high	Fast
	Baluti	Black shale and argillaceous - silty - sandy mudstone, with anhydrite and carbonate interbeds	High, serrated	Low, serrated	Very low, serrated	Slow, serrated
Kurra Chine Top	upper Kurra Chine	Massive to interbedded anhydrite and carbonate	Low – very low and clean	High to moderate, serrated	High – very high	Very fast
Geli Khana Top	basal Kurra Chine	Thin carbonate beds change upwards to anhydrite	Low and serrated	Low to moderate, serrated	Low to moderate	Fast
	Upper Geli Khana	Massive carbonate, predominantly limestone	Low and clean	Moderate to high, serrated	Moderate	Fast
Geli Khana Base	Lower Geli Khana	Argillaceous carbonate with shale and anhydrite interbeds	Moderate, serrated	Low to moderate, serrated	Low to moderate, serrated	Moderate, serrated
	Beduh	Shale and calcareous claystone	High	Low	Low	Slow
Chia Zairi Top	Mirga Mir	Calcareous claystone to clayey carbonate	Moderate, serrated	Moderate, serrated	Low to moderate	Moderate slow
	uppermost Chia Zairi	Clean massive carbonate (limestone)	Low and clean	Moderate high, serrated	Moderate high	Fast
Chia Zairi Base	basal Chia Zairi	Clayey carbonate changes upwards to clean limestone	High	Low, serrated	Low-moderate, serrated	Moderate, serrated
	uppermost Harur	Clean limestone, more argillaceous downward	Low and clean	High and clean to serrated	Moderate high	Slow

Table 1. Lithology and log character summary for key Upper Paleozoic - Triassic stratigraphic surfaces.

Stratigraphic Surface	Overlying / Underlying Rock	Lithology	GR (Gamma-Ray)	RES (Resistivity)	RHOB (Density)	DTC (Sonic) (comp. wave travel time us/ft)
Gotnia Group Top	basal Chia Gara	Thinly bedded organic-rich calcareous shale	Very high and cleans upward	Low and serrated	Low and serrated	Slow and serrated
	Gotnia, Barsarin or Najmah	Massive anhydrite, basin-filling carbonate or Najmah shallow marine limestone	Low and clean	High, serrated	Moderate high to very high	Fast
Sargelu-Naokelekan Top	lower Gotnia, Barsarin or Najmah	interbedded anhydrite argillaceous, sandy or clean carbonate	Low – moderate	Low to moderate, serrated	High or moderate high	Moderate fast
	Naokelekan	Extremely organic-rich black shale with thin limestone interbeds	Very high, serrated	Low and serrated	Low and serrated	Slow and serrated
Sehkaniyan Top	Lower Sargelu	Bedded limestone, may contain anhydrite interbeds	Low and increase upwards	Moderate high, decrease upwards, serrated	Low to moderate high, serrated	Moderate fast
	Alan	Massive anhydrite or with halite	Very low and clean	Very high or high	Very high	Very Fast
Sarki Top	Adaiyah	Interbedded anhydrite and carbonate	Low, serrated	Moderate-high, serrated	Moderate-high, serrated	High
	Upper Sarki	Clean and massive carbonate (often dolostone) with minor anhydrite interbeds	Low	Low moderate	Moderate-high	Moderate - fast

Table 2. Lithology and log character summary for key Jurassic stratigraphic surfaces.

Stratigraphic Surface	Overlying / Underlying Rock	Lithology	GR (Gamma-Ray)	RES (Resistivity)	RHOB (Density)	DTC (Sonic) (comp. wave travel time us/ft)
Lower Fars (Fatha) Top	Injana (Mid-Upr Fars)	Fluvial-alluvial fine-coarse clastics	Moderate	Moderate	Low, often no RHOB data	Slow and serrated
	Lower Fars (Fatha)	Multiple cycles of evaporite (gypsum, halite) anhydrite-carbonate-clastics	Low-moderate, serrated	Low-high, serrated	Low – high, serrated	Moderate-fast, serrated
Pila Spi Group Top	Euphrates, Kirkuk or Lower Fars	Shallow marine carbonate or evaporite-carbonate interbeds	Low-moderate, serrated	Low-moderate, serrated	High-moderate, serrated	Moderate fast
	Pila Spi or Jaddala	Shallow marine carbonate or shelfal limestone	Low, clean	Low - high	Moderate high	Fast
Kolosh Group Top	Gercus	Marginal to non-marine red beds clastics	Low and serrated	Low-moderate	Low to moderate, serrated	Moderate fast, serrated
	Khurmala	Shallow marine carbonate	Low and clean, slightly serrated	Low	Moderate high	Moderate Fast
Shiranish Group Top	Kolosh or Aaliji	Paleocene shallowing upward fine clastics	Low-moderate, serrated	Low, serrated	Low, serrated	Very slow
	Shiranish or Tanjero or Bekhme	Late Cretaceous shallow to deep marine carbonate or clastics (Tanjero)	Low, moderate clean	Low, moderate clean	Low-moderate	Slow, serrated
Upper Qamchuqa Top	Dokan or basal Kometan	Shelfal to deep marine carbonate	High, spike at base	Low, serrated	Low	Slow
	Upper Qamchuqa	Shallow marine carbonate, often dolostone	Low-moderate, serrated	Low-moderate, serrated	Moderate high	Moderate fast
Lower Qamchuqa Top	Upper Sarmord	Clayey-silty carbonate or calcareous shale	Moderate high, serrated	Low-moderate, serrated	Moderate high	Moderate, serrated
	Lower Qamchuqa	Shallow marine carbonate	Low and clean	Low-moderate, serrated	Moderate high	Moderate fast

Table 3. Lithology and log character summary for key Cretaceous to Cenozoic stratigraphic surfaces.