Chapter

Chemostratigraphy of Paleozoic Carbonates in the Western Belt (Peninsular Malaysia): A Case Study on the Kinta Limestone

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Abstract

The Peninsular Malaysia is divided into Western, Central, and Eastern tectonostratigraphic belts based on major geological and geophysical phenomena. The Kinta Limestone is a Paleozoic succession located within the Western Belt. Due to structural and tectonothermal complexity, the sedimentological and paleontological works in these carbonates have proven to be problematic unless combined with geochemical approach. Thus, the current study has integrated stratigraphical, sedimentological, and geochemical studies to assess the lithofacies variations and to interpret the depositional environments. An intensive fieldwork has been carried out in order to assess the extent of metamorphism and to locate the less altered sections for further studies. Three boreholes have been drilled on N-S transect of the Kinta Valley recovering a 360 m core. The core description, the mineralogical analysis, and the geochemical analyses including major and trace elements and organic carbon contents have allowed for a significant advancement of the knowledge existing on this basin. The obtained results have indicated that the Kinta Limestone is chiefly composed of carbonate mudstones, siltstones, shales, and minor cherty units. It preserves the main sedimentary features from metamorphism, especially in the northern part of the Kinta Valley. The detrital siliciclastic debris is minimum in the limestones. The overall dominance of fine-grained textures, the lacking of detrital siliciclastic deposits, presence of bedded cherts, and high organic carbon content outlined by geochemistry and the occurrence of uncommon benthic fauna have suggested the deposition in a slope environment with low energy and low oxygen content. The lithological changes from carbonate to siliciclastic deposits have outlined the occurrence of sea level fluctuations in the Paleozoic. The various analyses combined with chemostratigraphy, an independent of type locality and stratotype, enable to interpret the depositional environment of the Kinta Limestone. Thus, it can be useful to correlate to other formations in or similar types of basins in the southeast Asia.

Keywords: Kinta Limestone, Paleozoic, chemostratigraphy, Kinta Valley

1. Introduction

This chapter contains primary research data from a research project conducted on the stratigraphy and sedimentology of the Kinta Limestone. It has attempted to incorporate reviews on the stratigraphy and tectonic evolution of the Peninsular. It is widely accepted that the Kinta Limestone is one of the massive carbonate deposits which has longer temporal extension of Silurian to Permian and spatially covers the central part of the Western Belt of Peninsular Malaysia. In this contribution we have attempted to use relict primary sedimentary textures combined with geochemical signatures of cored and outcropped sections to interpret the environment of deposition and prevailed conditions during the deposition of the Kinta Limestone.

1.1 Geologic and stratigraphic setting of the Southeast Asia

Peninsular Malaysia is located in the southern-most tip of Asia Mainland (**Figure 1A** and **B**). It covers a total area of 130,268 km^2 and forms part of the Sundaland with the number of smaller islands emerging from the shallow seas. It is elongated in NNW-SSE direction and characterized by a dense network of streams

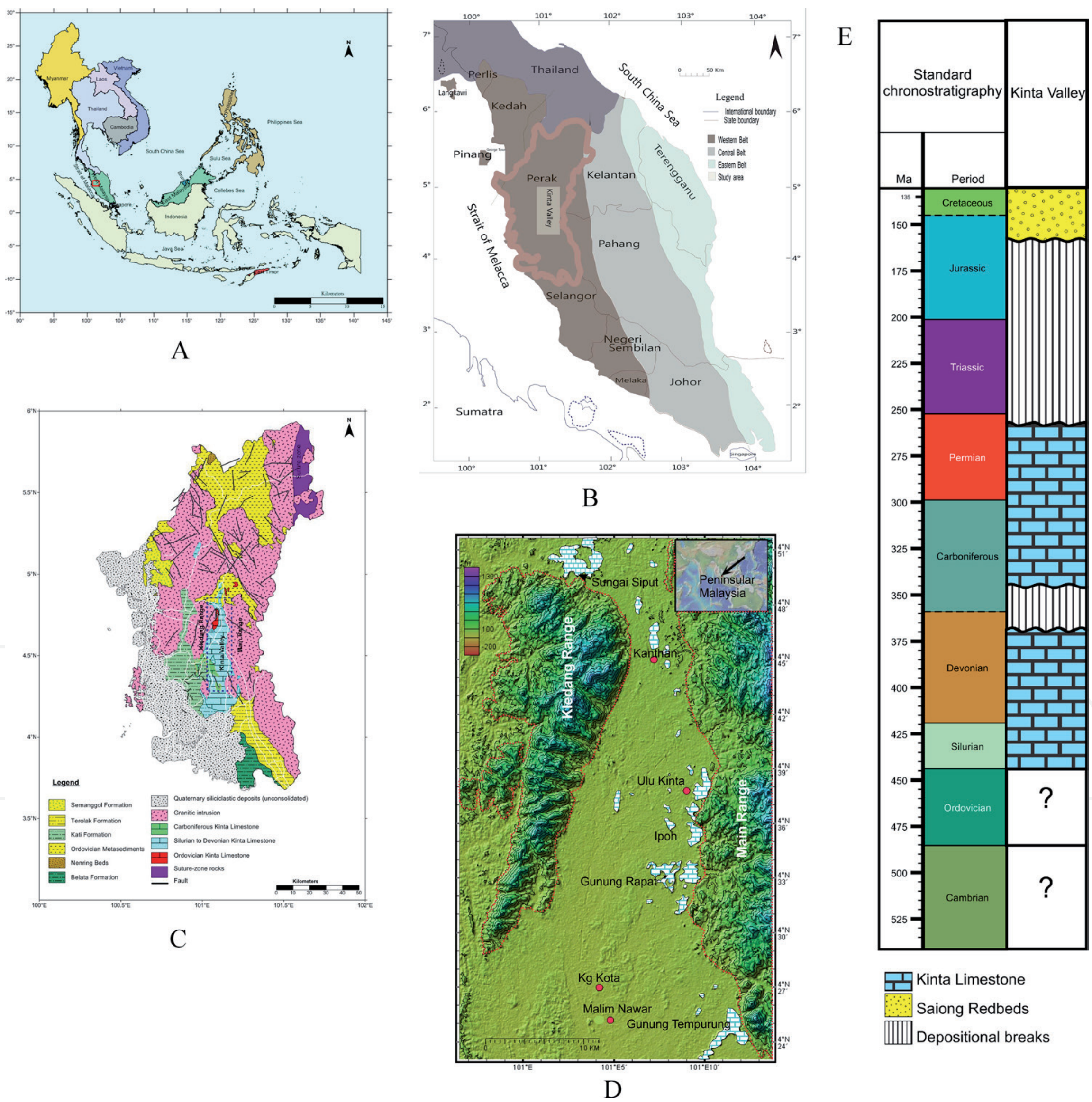

Figure 1.
Location map of the study area with respect to Southeast Asia regional map (A), tectonostratigraphic zonations of the Peninsular Malaysia (B), Geological map of the the Perak State (C), digital elevation model (D) of the the Kinta Valley area indicating the distribution of outcropped Kinta Limestone hills, and the composite stratigraphy of the Kinta Valley area (E) modified from [53]. Note that drilling locations are in the north (Sungai Siput) and in the south (Malim Nawar).

and rivers [1], which exposes older rocks, particularly in the Northwestern Domain of the Peninsula and the Kinta Valley.

Thick and widely spread carbonate deposition is common during the global sea level highstand [2–7]. During the Paleozoic, the global sea level was rising to a larger scale [8–10], during which the paleogeographic position of the Sibumasu was tropical to subtropical [11]. Most of the carbonate depositions were formed in tropical to subtropical latitudes, and some of the Phanerozoic carbonates even formed in lower latitudes [12]. The growth and the distribution of the carbonate successions in the south-eastern Asia region would not be an exception; hence, there should be a link with the paleogeographic evolution of the region during the Paleozoic times. Particularly, the limestone in Peninsular Malaysia might be strongly associated to the tectonic evolution of the peninsula during the opening-closure of the Paleo-Tethys. In this perspective, Peninsular Malaysia is made of two continental blocks, the Gondwana-derived Sibumasu and Indochina terranes, which come together in the Late Triassic. According to Metcalfe [13], the boundary between the Sibumasu and Indochina terranes was marked by the closure of the Paleo-Tethys Ocean and was evident in the Bentong-Raub Suture Zone, representing a segment of the main Devonian-Middle Triassic Paleo-Tethys Ocean. The present-day Peninsular Malaysia is formed from these two terranes and is divided into three main different tectonostratigraphic zones, having a characteristic stratigraphy related to their tectonic history [14, 15]. This research has been carried out in the Western Belt, which includes the Northwestern Domain, which was part of the north-western Australian Gondwanaland during the Late Paleozoic. During the Late Permian and during the Middle to Late Cretaceous, two compressional events were reported in the Peninsular Malaysia [16]. Tectonothermal events have left confusing structures of folding to secondary sedimentary structures such as slumps. The tectonic uplift coupled with isostatic movements has caused considerable loss of sediment thickness on the Pre-Permian and Permian rocks of the peninsula, due to erosion, resulting in the deposition of younger sequences such as the Semanggol Formation [11]. However, the stratigraphic boundaries of the major Paleozoic formations of the Western Belt of Peninsular Malaysia are not clearly known due to the complex structural, thermal events, and lacking accessible stratigraphic units. This is even more complicated in the Paleozoic carbonates of the Kinta Valley, which are represented by scattered protruding limestone tower hills. Major portion of these limestone hills are covered by thick Quaternary deposits and surrounded by the massive granite bodies in the east and west marked by the elevated regions on the map (**Figure 1C** and **D**).

1.2 Historical development on the stratigraphy of the Kinta Valley

Peninsular Malaysia can be subdivided into three north-south trending belts (**Figure 1B**) with characteristic stratigraphy, structure, magmatism, geophysical signatures, and evolutional paths [11, 14, 17]. The stratigraphic classification for the Paleozoic successions of the peninsula comprises 42 formations [14, 18], and few of them have been revised to establish new lithostratigraphic units [14, 19]. For instance, the lower Paleozoic rocks are found in the western part of the peninsula, whereas upper Paleozoic successions are common in all the three stratigraphic belts of the peninsula [14, 18]. The Kinta Limestone (**Figure 1E**) has been assigned to varying geological ages depending on its geographic locations ([20] and references therein) and other authors cited in [14, 18, 21, 22]. Among the earliest to share their findings on the geology of Perak State were Errington and Wood ([23] and references therein). The first attempt to establish the lithologic succession of the Kinta Valley was made by De Morgan [24] followed by Wray [25], who classified the lithology of the Kinta Valley into four rock types in which the crystalline limestone was overlain by a large series of beds comprising gneiss, quartzite, schist, and sandstone as cited in Ingham and Bradford [23].

In 1903, another view from Collet had emerged where he believed that the limestone is younger than the other sedimentary beds ([23] and reference therein). However, Scrivenor [26] has published a study with the crystalline limestone as the oldest unit compared to the Mesozoic granite, phyllites, and quartzite. More specifically, Scrivenor [27] considered the limestone (carboniferous) to be older than the phyllites and quartzites in which he addressed the clays and boulder clays as "Younger Gondwana Rocks." However, in 1917, Jones disagreed with the view of Scrivenor [27] specifically on the source and nature of the boulder clays and proposed a sequence in which the limestone belongs to Permo-carboniferous periods [23]. Thus, in Jones' lithological succession, the crystallized limestone was stated to be underlying the schist, phyllites, quartzites, indurated shales, granites, and alluvial deposits, which was consistent with Scrivenor [27]. It is also mentioned in Ingham and Bradford [23] that Cameron [28] and Cameron [29] had disagreed and proposed a new geological succession. This is simply to highlight how the established stratigraphy of the peninsular, particularly the Kinta Valley, was complex and debated among researchers for a century and half.

In the study area, the chemical characters of the rocks have been used to infer their depositional conditions and to develop correlation schemes. Redox-sensitive elements, coupled with major and trace element analyses have been carried out to assess the Kinta Limestone at the level of depth that this project has reached.

2. Stratigraphy and geochemical analyses

2.1 Stratigraphy

In this chapter, we present our findings on all the accessible outcrops along a north-south transect of the Kinta Valley and the stratigraphic data from three shallow boreholes drilled into the Kinta Limestone. The study has included all major outcrops from Sungai Siput through to Malim Nawar (**Figure 1D**). A detailed fieldwork has allowed us to choose selected outcrops near to the Sungai Siput, enabling to infer the depositional conditions of the Kinta Limestone. These hills are outliers surrounded by siliciclastic deposits, relatively less effected by metamorphism, and have exceptionally preserved primary sedimentary features [30]. Two boreholes, SGS-01 and SGS-02, were drilled and retrieved a total of 126.98 m of cores. These boreholes were approximately drilled to a lateral distance of 1 km from each other. A third borehole, MNR-03, was drilled further to the south of the Kinta Valley in Malim Nawar (**Figure 1D**) and retrieved the deepest core, at 232.82 m vertical depth. This is an area where most of the fossiliferous surface limestone sites were reported in the literature. The three boreholes give a total of ~360 m of core recovery, which enabled detailed lithofacies and micropaleontological studies of the Kinta Limestone.

The lithofacies in the northern part of the Kinta Valley is mainly dominated by dark to black carbonate mudstone with black shale beds and siltstone intervals, particularly at the base of the boreholes SGS-01 and SGS-02. The southern section of the Kinta Limestone contains calcitic limestone with minor clastic intervals. The southern section has relatively coarser-grained texture than the northern section lithofacies of the Kinta Limestone. It has also been revealed that the Kinta Limestone has older sections in the present north and younger sections in the present south of the Kinta Valley [31].

2.2 Geochemical analysis

2.2.1 Inorganic geochemistry

In this research, X-ray diffraction (XRD) and X-ray fluoresces (XRF) were used for mineralogical, elemental and oxide analysis of selected samples. X-ray diffraction (XRD) is one of the basic tools in the geochemical analyses of rock samples of limestones and mudrocks [32]. The samples were prepared in the Material Laboratory of Universiti Teknologi PETRONAS. The rock samples were pulverized to grain-size less than 63 μm in order to obtain a well-homogenized powder, according to the methods and recommendations of Tucker [32]. The powder was dried in an electric oven at 49.3°C for about 24 hours to remove the moisture content. Once the samples were dried, they have been analyzed using the XRD machine, in which the diffraction patterns have been interpreted using dedicated software and databases [33, 34]. The analyses and interpretations of the XRD results were based on the procedures stated by Tucker [32] and Dong [34].

There is an increasing trend in the application of XRF techniques in the characterization of carbonate rocks, particularly for elemental chemostratigraphy of carbonates and useful tool to study the stratigraphic successions. XRF is the preferred technique for the analysis of major and minor elements, such as Si, Al, Mg, Ca, K, Na, Ti, S, and P in siliciclastic rocks and also for trace elements such as Pb, Z, Cd, Cr, and Mn. An energy-dispersive XRF system was applied in this research since it has the ability to measure all elements over a spectrum of wavelength. A total of 12 representative outcrop samples were collected from Kanthan, Malim Nawar, Ulu Kinta, and around Kampar areas (**Figure 1D**) for geochemical analysis using XRF. Forty-four borehole samples were analyzed for elements and oxides. These samples were collected to represent the major lithofacies variations noted during core description. The sample distribution is indicated in **Table 1**.

The samples were mainly carbonate rocks except four siliciclastic rock samples, which were included from the northern part of the Kinta Valley. The results are plotted for the samples, which have values greater than zero based on the detection limits of the testing tools.

2.2.2 Organic geochemistry

In a broader sense, organic geochemistry deals with the fate of carbon, in all its variety of chemical forms in the earth system [35]. Many organic matters can be incorporated into sedimentary rocks and preserved for millions of years. Kennedy et al. [36] showed that the preservation of organic carbon is most commonly controlled by oceanographic regulation of bottom-water oxygenation and/or biological productivity. This relationship could be used to evaluate the organic content of sedimentary rocks and the records on paleowater conditions such as energy level, water depth, rate of deposition, and other related paleo-oceanographic parameters.

Sample source	Quantity
Outcrop	12
SGS-01	10
SGS-02	14
MNR-03	20

Table 1.
Number of samples for XRF analysis taken from the respective localities.

Total organic carbon (TOC) content and pyrolysis analysis using Source Rock Analyzer were carried for a total of 60 samples. These analyses were selected in order to support both the interpretation of the depositional environment (the vitrinite reflectance, distribution of TOC with grain size); the paleothermal evaluation (Tmax that is compared with the temperature from the CAI). The TOC measurement provides clue on the paleodepositional conditions such as oxic and anoxic, indicating also the rate of deposition and level of surface organic productivity.

2.3 Chemostratigraphy

Chemostratigraphy is application of sedimentary geochemistry to stratigraphy. It is highly linked to lithostratigraphy since the major lithologic differences are connected to changes in the importance or balance between different geochemical reservoirs. It is based on the theory that the chemical and physical composition of sea water varies through geological time. These changes have been recorded by the chemical composition of the sediments (by major and trace element distribution) and by the isotopic ratios of particular elements [37, 38]. The seawater composition is considered homogenous for a certain geological time, since the mixing rate of seawater is relatively short; therefore, geochemical variations have global implications [37]. The collected outcrop and core samples were analyzed for major and trace elements. The main interest in the analytical techniques was to characterize the rock units in terms of elemental concentration and ratios and to uncover any systematic trends. The use of changes in elemental composition of sediments of the outcrop and borehole samples has enabled to establish a chemostratigraphic zonation. Thus, geochemical analysis is used in conjunction with petrographic data in the selection of samples for the establishment of chemostratigraphy and interpretation of the paleoenvironment. Chemical stratigraphy is a study on the variation of chemistry within the sediments or sedimentary sequences for stratigraphic correlations [39]. It is a tool that uses the changes in elemental composition of sediments to characterize sedimentary sequences and to spatially extend this characterization between outcropping sections or wells to form a chemostratigraphic correlation. This characterization enables the identification of chemostratigraphic packages and units on the basis of elemental concentrations, ratios, and their systematic trends. Chemostratigraphy is a relatively young subdiscipline in the stratigraphy, and it is also a new attempt to apply it on the Kinta Limestone.

3. Results

3.1 Lithostratigraphy of the Kinta Limestone

The surface lithology of the Kinta Valley is dominated by the granites, overlain by Quaternary-Recent deposits (**Figure 1C**). Paleozoic deposits occur as isolated exposures. Three types of sedimentary lithologies namely, limestone lithofacies followed by siltstone and thin black shale beds in the order of decreasing proportions, were identified based on outcrop, core, and petrographic studies. Rarely bedded chert units also occurred in specific localities, for example, in the Sungai Siput section. The Sungai Siput section, located in the northern part of the Kinta Valley, is dominated by fine-grained, light-to-dark gray to black, thinly laminated carbonate mudstone. It shows a sharp contact with the light-gray and dark-colored carbonate mudstone, cherts, and the black shale lithofacies. These lithofacies types at place exhibit slump structures. The section in Sungai Siput site is less affected by dissolution; however, it is highly compacted and stylolitized if compared with the other sections of the valley. The samples from the dark gray intervals of the Sungai Siput sections were found to be richer in phosphatic microfossils in contrary to the other lithofacies [31]. When compared with the very thick carbonate mudstone beds (many tens of meters thick), relatively thin black shale (2 m thick) in SGS-01 borehole was typical of this unit. The light brownish-gray, fine-grained muddy siltstone lithofacies occurs in the Sungai Siput sections of SGS-01 and SGS-02. This muddy siltstone underlying the carbonate mudstone is a dominant lithofacies intercepted in boreholes SGS-01 and SGS-02, but not encountered in borehole MNR-03 in the south of the Kinta Valley. The siltstone is highly affected by fractures and compositionally dominated by quartz. An outcrop section located further south-east of the Sungai Siput (Kanthan) is characterized by light gray, fine-grained, subhorizontally bedded thin to thick intercalations of carbonate mudstones. It contained dark-colored fine-grained material on the contact planes of the bedding surfaces. Minor whitish to white pinkish colored lithofacies was observed in the section near the granite contacts. The degree of lithofacies heterogeneity is less than the Sungai Siput section. Syn-depositional sedimentary structures, including slumps and thin bedding with sharp contact surfaces, were ubiquitous in the intervals dominated by the black shale interbeds and dark gray carbonate mudstone of the Sungai Siput section. Other sections, located in the eastern sector of the valley, are found to be entirely dominated by metamorphosed units, where most of the sedimentary features have been obliterated. There is no observable lithological variation on the metamorphosed carbonate hills in the western foothill of the Main Range Granite such as Gunung Rapat (**Figure 1C**). Rather, coarser and homogeneously calcitic marble occurs in these areas. Along the contact of planes of the metamorphosed carbonates, pyrolusite mineralization was noted. Faults and joints are also observed with well-developed dissolution cavities and large-scale caves (e.g., Kek Lok Tong, Gua Tempurung). Three sets of sealed fracture networks filled with calcite cement also occurred. The degree of surficial weathering has impacted the lithology variably with respect to geographic locations in the Kinta Valley. For instance, the dissolution is intensive near to the granitic intrusions, where metamorphism is higher and in the southern part of the valley, where subsurface pinnacles were found.

The siliciclastic interval of the cored sections of the Kinta Limestone shows higher gamma-ray (GR) values, whereas the limestone intervals are characterized by low values and smooth gamma ray log curves. The density log of the section is also in agreement with GR logs in such a way that the higher GR values are associated with high density. The SP log was not diagnostic, except for its indication of the occurrence of a porous siliciclastic interval at the base of the SGS-02 borehole. Caliper log detected the lithological contacts between the limestone and the siltstone intervals, which was denoted by caving in the siliciclastic intervals, while the limestone portrayed a fairly smooth borehole environment, as the limestone is relatively compact.

3.2 Chemostratigraphy of the Kinta Limestone

The samples from borehole SGS-01 were collected based on the core description from top to bottom of the borehole at irregular intervals. The result shows the four elements (K, Si, Ni, and Al) are very low in concentration in the pure limestone sections. K, Si, Ni, and Al are present in high concentrations in the shale beds found from 9.87 to 13.43 m depth (**Figure 2**). These elements are also present in high concentrations from 40 down to 65 m depth. Moreover, all the four elements have shown slight variations along the vertical profile of the borehole with respect to lithologies (**Figure 3**).

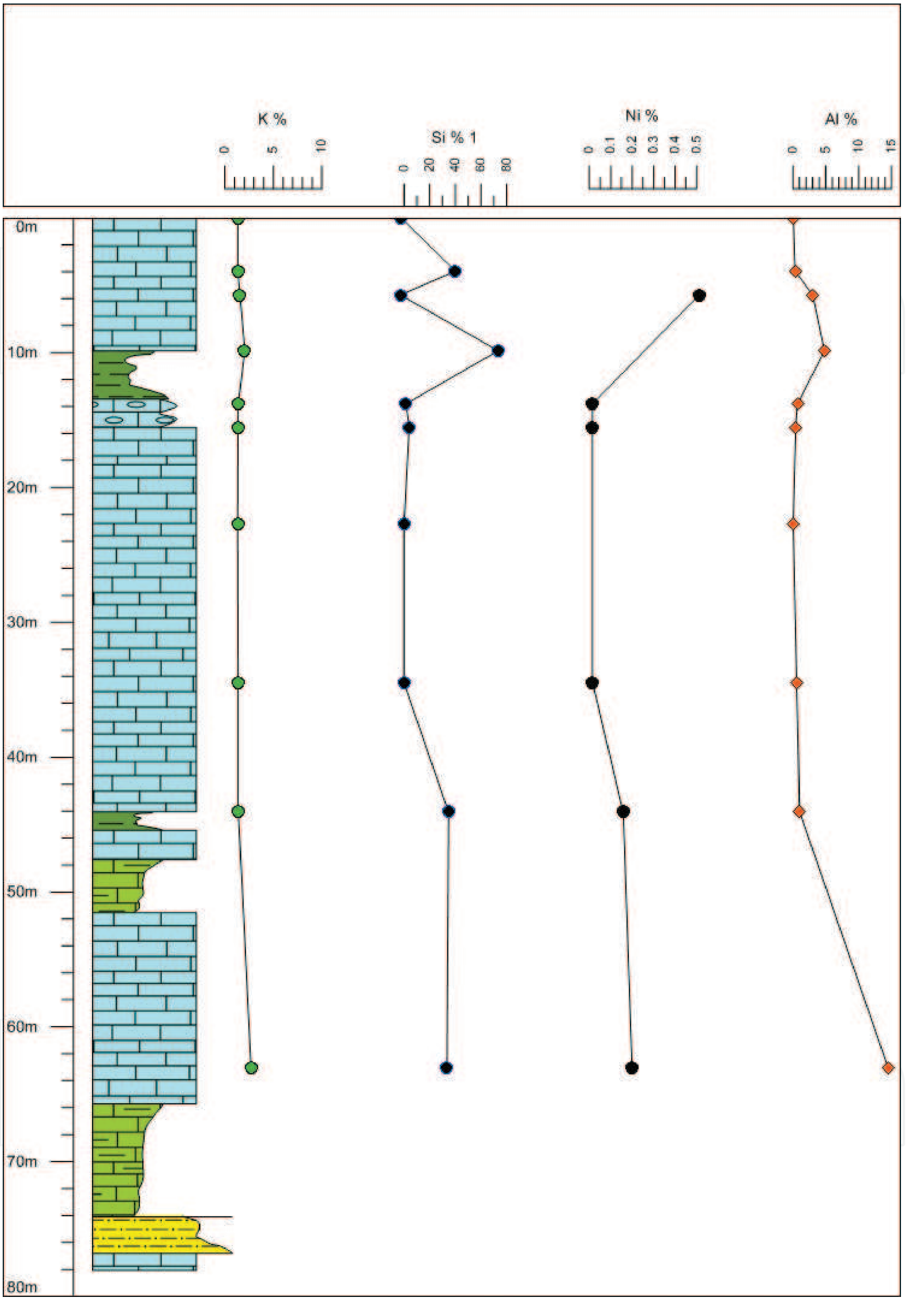

Figure 2.
Chemostratigraphic log of borehole SGS-01. Note that the variation of these K, Si, Ni, and Al along the vertical profile of the borehole.

Ca, Mg, Mn, Sr, Zr, and their ratios have shown a significant variation with depth and a wiggling pattern along the vertical section of the borehole (**Figure 4**). The Ca content of the carbonates is high, whereas Mg is low(less than 1 wt.%). Ca and Mg are among the major elements in the carbonate mineralogy, while Mn and Sr are minor but provide a clue of the postdepositional history of carbonate rocks. Si is lowest for carbonates but it is highest for the siliciclastic deposits of the

Figure 3.
Lithology legends for the lithostratigraphic logs in the boreholes. Note this legend is used throughout this chapter.

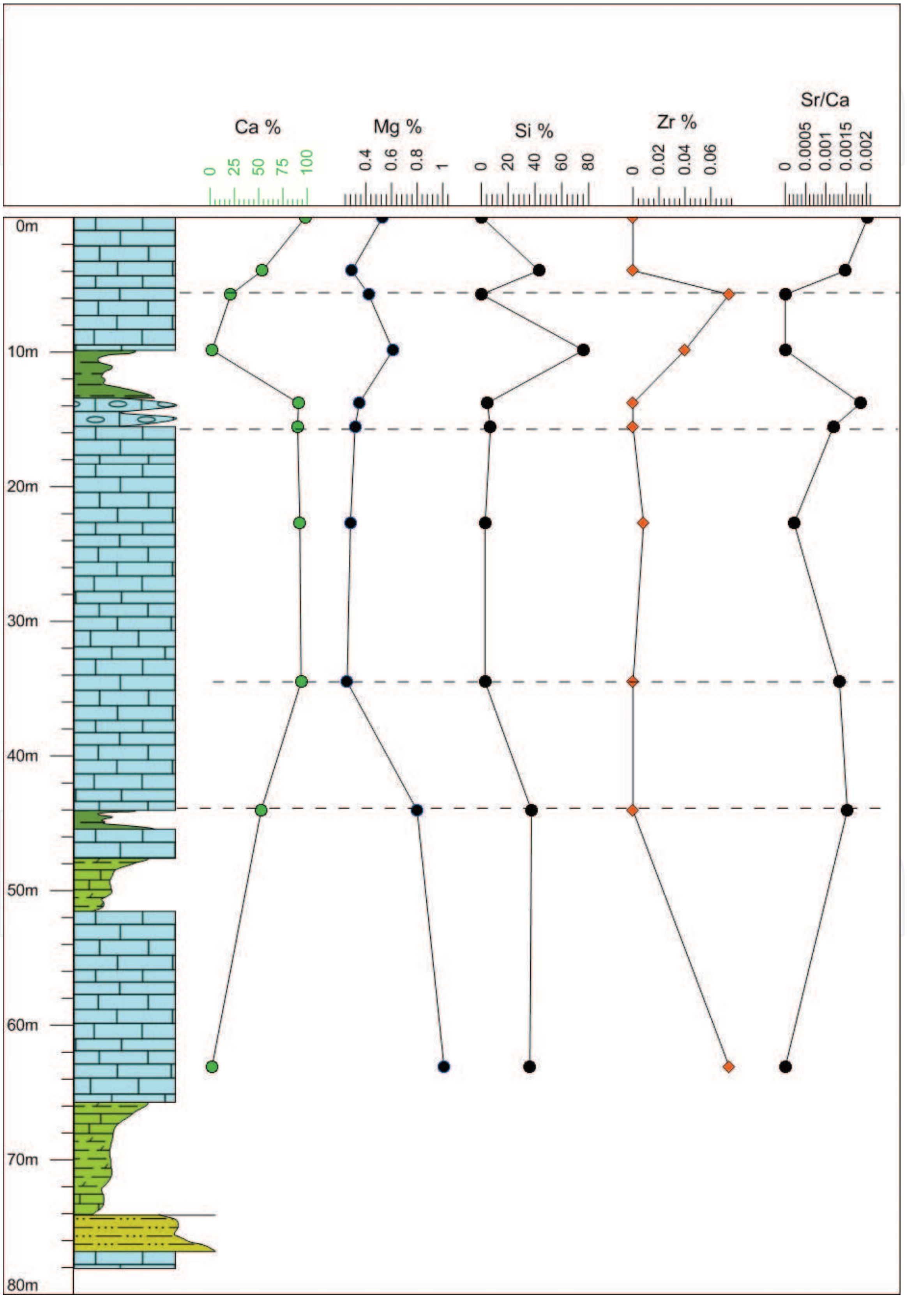

Figure 4.
Chemostratigraphy of the SGS-01 based on elemental concentrations and ratios. Note that there are a few chemical packages, which are characterized with similar chemical signatures for the displayed element and ratio data set.

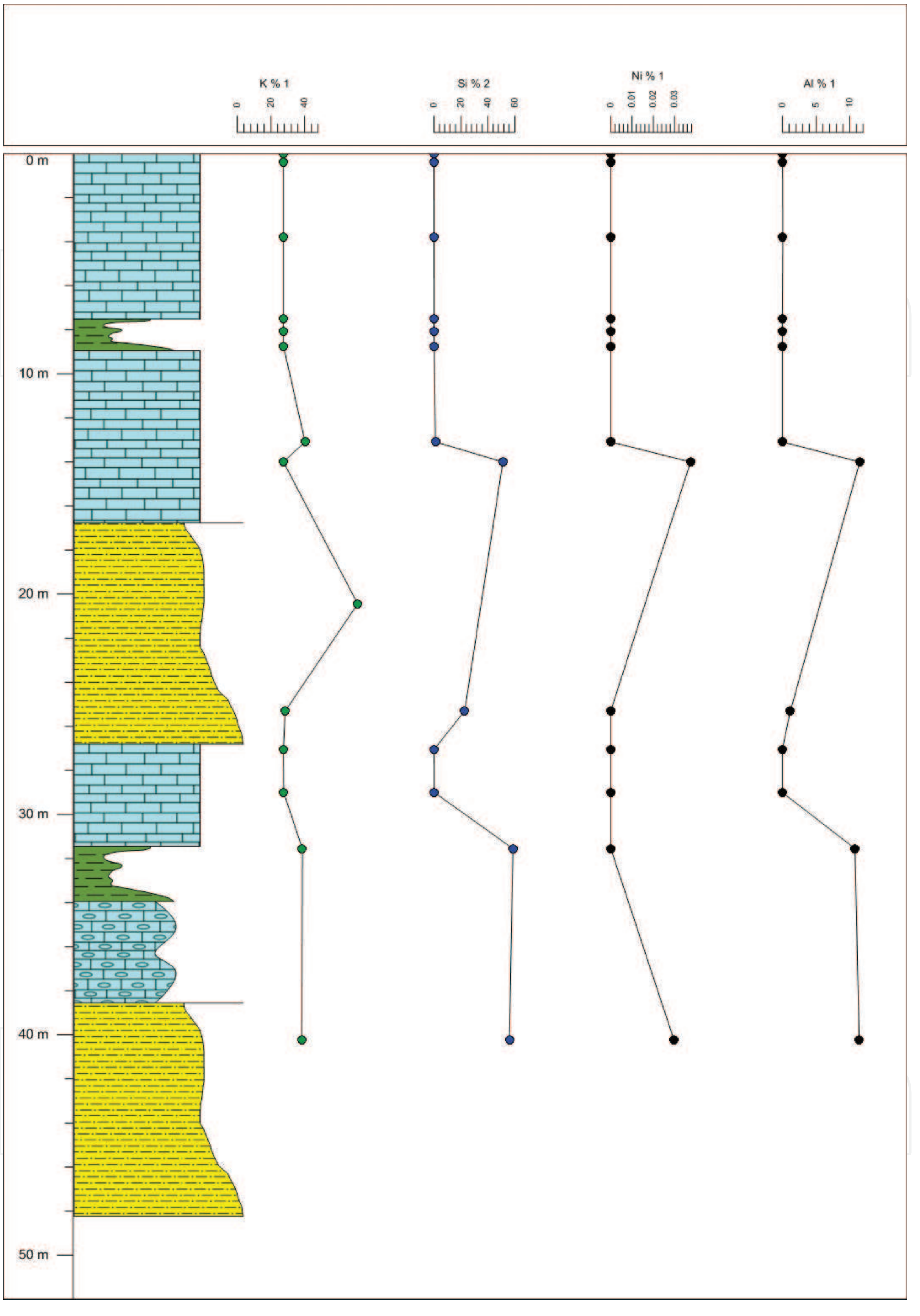

Figure 5.
Chemostratigraphic log of the borehole SGS-02. Note that the slight correlation of the elemental concentrations of the data set.

borehole. The Si content shows similar trends to the Zr content of the black shale intervals. Total carbon content (TOC) analysis of the samples shows that the black shale intervals have the highest concentration (4.93 wt.%) and lower TOC for the other lithofacies. The correlation with the lithological variations is marked, especially at the top of the SGS-01 section.

Although a slight difference in the lithological arrangement, the elemental concentration of K, Si, Ni, and Al in the borehole SGS-02, has been noted, it has shown similar trend as in borehole SGS-01. The concentration of K is higher in the siliciclastic lithofacies such as the shale and the siliceous carbonates (**Figure 5**). Si, Al, and Ni also followed a similar pattern in the siliciclastic intervals. These elements

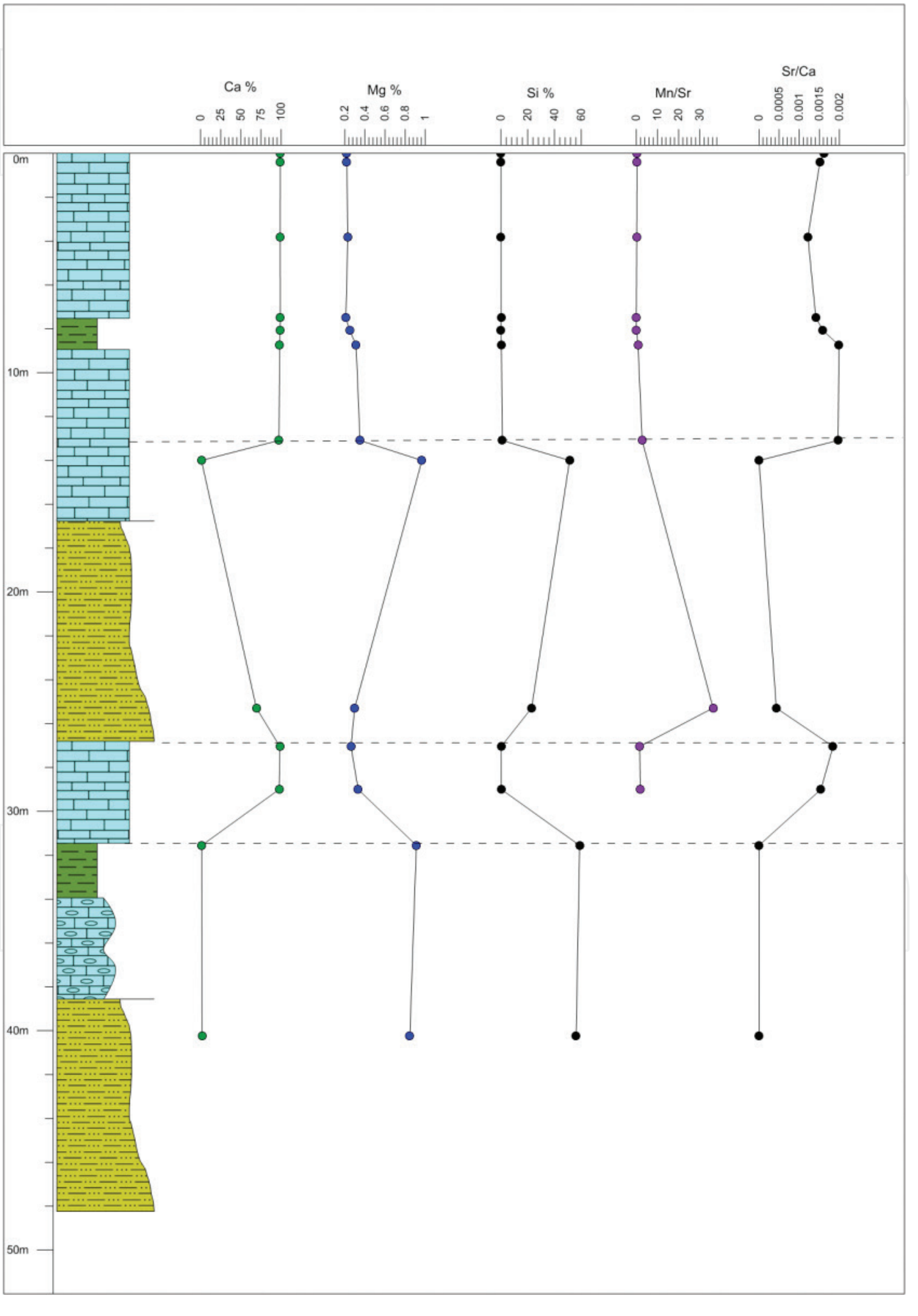

Figure 6.
Chemostratigraphy of SGS-02 based on elemental ratios. Note that there are four chemical packages, which showed different chemical signatures.

are either not present or found in very low concentrations in the purely limestone intervals. These variations reflect the lithofacies variation along the vertical profile of the borehole. These chemical signatures may have some implication for the depositional environment and diagenesis history of the section.

A plot of Ca, Mg, Si, Mn/Sr, and Sr/Ca with respect to depth is shown in **Figure 6**. The chemical signature has shown a shift at 13.16 m in all the elements and their

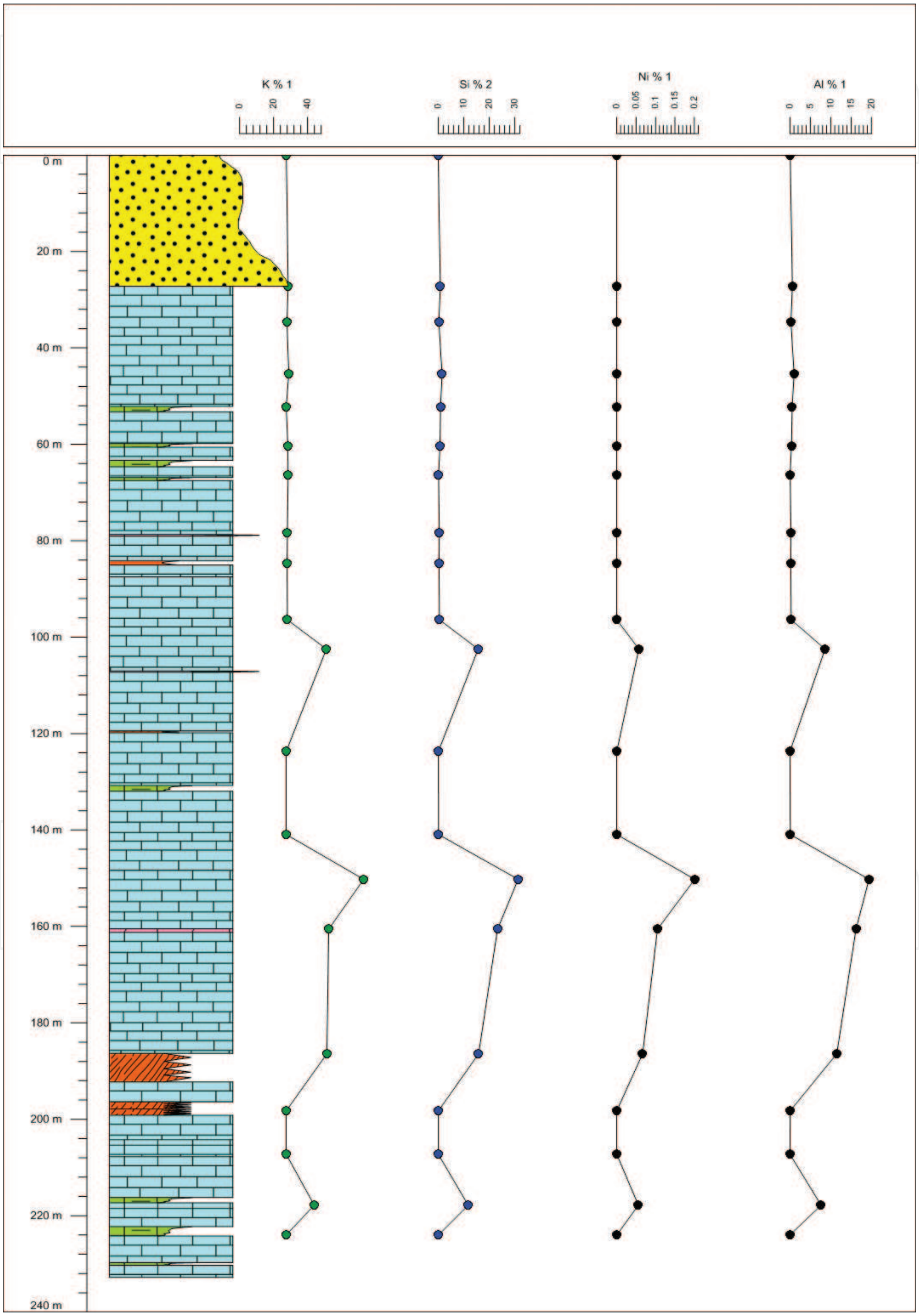

Figure 7.
Chemostratigraphic log of borehole MNR-03. Note the sharp increment of K, Si, Ni, and Al concentrations from 148 to 192 m depth. This depth was also noted having some indication of aerial exposure.

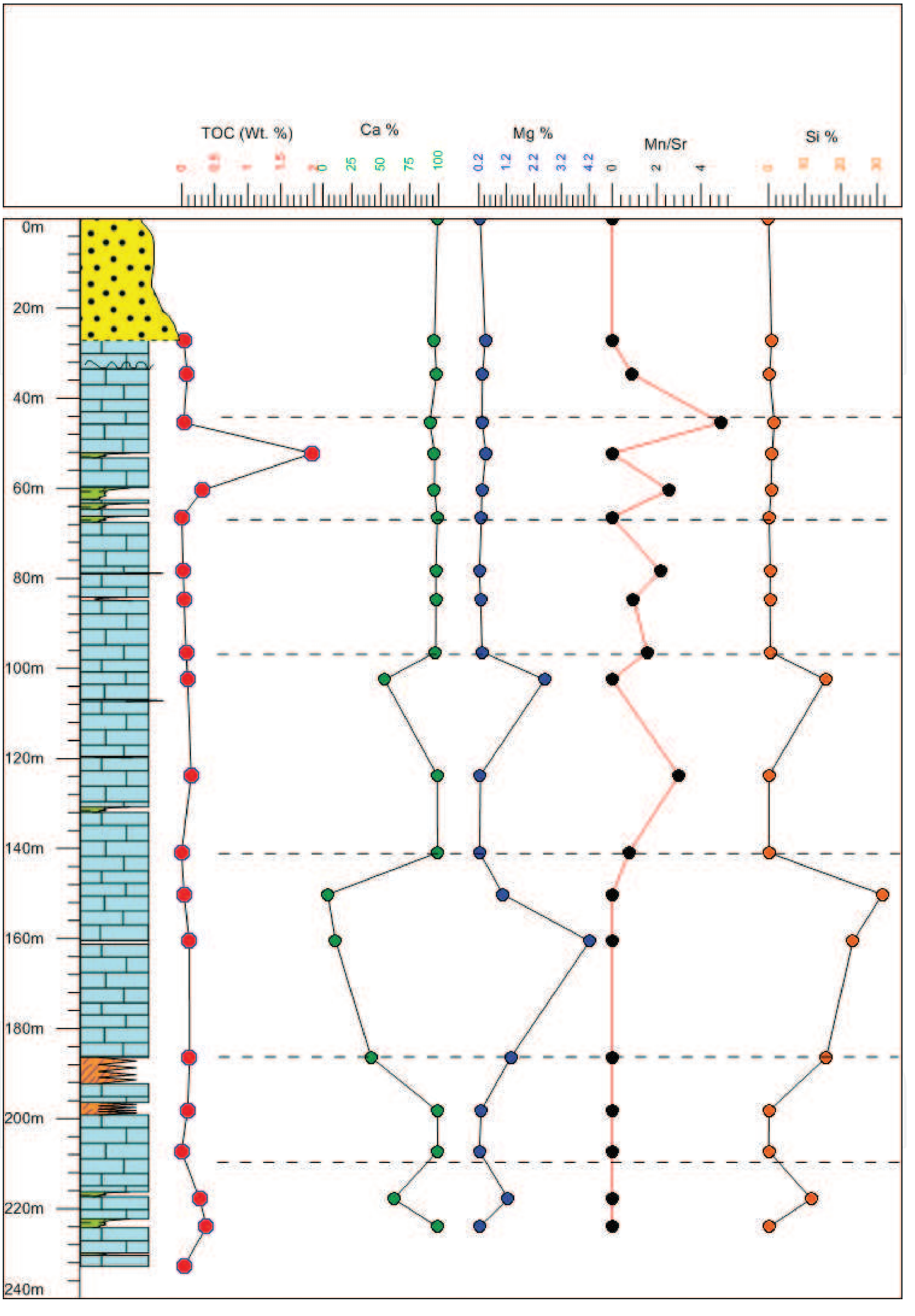

Figure 8.
Chemostratigraphy of the borehole MNR-03 based on elemental concentrations and ratios. Note the pattern of variation in the chemical signature of Ca, Mg, and Si from 148 m downhole to 192 m, where Ca showed decreasing trend, and Mg and Si are increasing until 192 m depth.

ratios. Another significant change of the chemical signature of the lithofacies has been observed to a depth of 26.75 m. Another equally important variation in the elemental signatures is shown at depths of 31 m. Ca is the highest concentration in the carbonate mudstone lithofacies, with little Mg and almost zero Si. These geochemical signatures disclose a direct correlation with the lithological variations.

The TOC is highest in the shale intervals at 7.5–9 m and remains flat in the other lithologies. It can be noted that there may be a possible link with the depositional environments and with chronology of the chemical signatures.

A thorough analysis of the elemental composition of the section from the Kampar area (borehole MNR-03) has showed a particular pattern of K, Si, Ni, and Al. A unique signature with depth from top toward the bottom was depicted by the elemental concentration of the selected elements (**Figure 7**). The limestone in the topmost 100 m of the borehole is almost pure. It contains a very low concentration of K, Si, Ni, and Al. Minute peaks of the four elements occurred from 96 to 115 m. A major increase in the elemental concentration of the four elements occurred from 148 to 192 m. This is then followed by a section of pure limestones with a small shift of the four elements until a depth of 217 m. These geochemical signatures are relevant in order to discuss the depositional and postdepositional events.

For the southern part of the Kinta Limestone, the Ca, Mg, and Si elemental concentration showed some enrichment downhole. Ca, Mg, and Si remain somehow constant until the depth of 96 m. From 96 to 148 m, there is a slight variation in all the elemental and ratios. The trend of Ca and Mg is in inverse relationship. From 148 m downhole showed main decrease in Ca and increase of the others, while the Mn/Sr ratio remains constant. The TOC is generally low and only showed high peak at 45–60 m depth (**Figure 8**). These variations may provide some clues about depositional and postdepositional processes on the studied sections.

4. Discussion

The lithofacies distribution in the Kinta Valley depicts important clues for the interpretation of depositional environments. For instance, the lithofacies from the Sungai Siput sections of the Kinta Limestone is mainly dominated by fine-grained carbonate mudstones. In addition to the carbonate mudstones, siltstones, black shales, and chert beds have been described from the northern part of the Kinta Valley. These lithofacies have textural attributes and field distributions, suggesting low-energy depositional environment. To the east of the northern Kinta Valley, the presence of schists was noted, thus providing some implication to infer possible paleodepocenter of the Kinta Limestone. Thus, the textural features of the lithofacies encountered in the present-day northern and north-eastern part of the Kinta Valley imply that the lithofacies reflect a certain type of paleobasinal configuration during their deposition.

The lithofacies colors of the Kinta Limestone varied from light gray to dark and black in the northern part of the valley. This has been used as one of the clues that may indicate the deposition of this type of lithofacies in a condition where and when it is conducive for the incorporation of organic matter. It has been found to be rich in TOC and interpreted that the color variation was partly controlled by the organic content of the rocks. This may indicate that the limestone was deposited in an environment that prohibited oxidation of the organic contents that were incorporated into the sediments during deposition. Conditions for this type of preservation are common either in a restricted lagoon or in a deeper marine setting where less oxygen is available, which led to the survival of limited scavengers and decomposers. Therefore, the best fit for this type of depositional setting would be deeper part of a slope in the northern end of the Kinta Valley; and the slope was shallower toward the south of the Kinta Valley. The presence of shell fragments in the Sungai Siput (N) limestone has an indication that the Kinta Limestone was deposited at a depth shallower than the CCD, since the dissolution of shell fragments made of calcium carbonate is expected to increase with increase in hydrostatic pressure and decrease in temperature with increased water depth. Thus, the origin of the Kinta Limestone should be biogenic with minimal chemogenic input. This is consistent with the observation in the modern carbonates, which are rich in skeletal components of marine organisms; and this was believed to be true in the Phanerozoic time as well [40]. In summary, the texture, color, TOC, and lithofacies analysis of the Kinta Limestone indicates low energy, calm, and varying paleodepositional settings. It was found that most of the lithofacies textures, TOC, biofauna, and color showed that the Devonian-Carboniferous interval of the Kinta Limestone was deposited in a deeper environment, perhaps with limited oxygen supply.

Sedimentary structures could be depositional, which are formed during deposition, or postdepositional, which are formed after deposition of the sediments during the burial stage. The depositional structures are known to be primary, and the postdepositional structures are secondary. The primary structures in the Kinta Limestone are the thinly bedded, dark gray to black carbonate mudstones in the Sungai Siput (N) and the chert laminae. The contact planes of the beddings are sharp, indicating a calm and less disturbed depositional environment. The slumps may signify that the Sungai Siput (N) section might be deposited in a sloping localized bathymetric variation with slight instability right after deposition. Structures that are similar to slump but difficult to confirm are also seen in the Kek Lok Tong areas. These structures are not used for the above inferred interpretation due to the fact that the lithofacies in this area is highly affected by contact metamorphism. This is reasonable as this area is in contact or in a short distance from the Main Range Granite, which is expected to have greater impact on the sedimentary rocks due to its huge source of heat for the metamorphism event. In the geological records, slumps commonly occurred in two locations, high up in the slope and lower down of the slope profile due to the susceptibility of slope facies to downslope creep [41]. The origin and use of the slump structures as indicators of paleoslope have been documented in many works [42–48]; thus, there is a consensus on their use for inferring the paleobathymetry and possible triggering means of the movement of the sediment on the paleoslope. The triggering mechanism could be failure of slope, which is driven by gravity or involvement of seismicity [44, 49]. Such kind of sedimentary structures are known as soft-sediment deformation structures, which provide keys in understanding the depositional history of sedimentary rocks. Soft-rock deformations are documented that they are created either during deposition or shortly after burial [50]. Slumps are common in mudstone, limestone, deposited on a steep slope. They are commonly faulted and folded. They can be indicative of fast deposition rate [51].

Studies on the Devonian-Carboniferous successions from the Northwestern Domain of Peninsular Malaysia indicated that there were shallow marine deposits with major regressive events during the latest Devonian [19]. This implies that a possible shift of depositional environments from shallow water to a deepening trend toward the northern Perak, where this study was conducted. Cocks et al. [52] indicated that there was a general shallow-water and cratonic areas during the Middle Paleozoic of the Sibumasu Terrane, except for deeper successions in the northern Perak. In addition, Meor and Lee [19] indicated that a deposition of thick red mudstone interbedded with silty sandstone in the Early Carboniferous might contradict the depositional break suggested in the Kinta Limestone [53].

Stylolites are the most visible postdepositional events on the cores and accessible outcrops of the Kinta Limestone. Stylolites are postdepositional irregular discontinuity surfaces, which are believed to have resulted from localized stress-induced dissolution features during burial or tectonic compression. The patterns, density, and size of the amplitude of the stylolites have implications on the amount of siliciclastic impurities and heterogeneity of the carbonates that would increase the chance of nucleation of the stylolite seams [54]. Thus, the stylolites in the Sungai Siput (N) section are more abundant than on any other part of the studied sections in the Kinta Valley. This also goes well with the lithological variation observed in the Sungai Siput section. The presence of the fine-grained siltstone, shale, and carbonate mudstone with bedded chert shows that the stylolites correlate with this heterogeneity. In addition, the stylolite may also show uplift (deeper burial so that there was high overburden) or be originated from compressive pressure. Stylolites are common in fine-grained sedimentary rocks affected by chemical dissolution. Chemical dissolution is also common in pelagic to hemipelagic sediments. This supports the contention that the depositional environment of the Kinta Limestone might be pelagic to hemipelagic.

In summary, all the primary and secondary structures discussed are consistently implied a variation in the paleobathymetry from the present-day north to the present-day south of the Kinta Valley. It was revealed that the northern part of the Kinta Valley was dominated with sedimentary structures, which indicated deposition in a steeply dipping slope, which was probably unstable during the upper Devonian to lower Carboniferous time. It was also learned that the environment to the present-day north of the Kinta Valley was favorable for deposition of fine-grained sediments, which are common in low-energy depositional environments. The bedded chert in the Sungai Siput (N) may also suggest that it was a primary deposition of silica-rich material in a low-energy, relatively deeper depositional environment. Moreover, its association with slump structures may also suggest its function as decollement surface during the soft-sediment deformation of the succession. It is also clear that the depositional environment was above CCD, however, at considerable depth of water.

On a general basis, the studied samples have shown that the variation of the major elements is directly related to the lithofacies types. The carbonates are found to be dominated in Ca and contain little Mg. However, they are found to be poor in silicate-derived elements such as Al, Si, and K. This variation may throw light to the condition and source of the sediments during the deposition of the lithofacies. Thus, the implication of the spatial chemical variation may have also temporal significance and indication that the lithofacies may still maintain primary sedimentary geochemical signatures that could have value in understanding the depositional environment and diagenetic processes.

The geochemical findings from different localities in the Kinta Valley provide clue for the establishment of chemostratigraphic correlations on the outcrops and borehole data sets. A generally trending variation of the chemical and lithological variation from the north to the south of the valley is a typical observation on the analyzed samples. These characteristics were reflected in the elemental ratio and oxides concentrations. Those variations make sense as the rocks are also found to be younger in the south than in the north [31]. Therefore, the variations may have some relation to the compositional variations of the Paleo-Tethys Ocean. The lateral and vertical variations of the chemical signature of the Kinta Limestone and its implication for depositional environment provide clues as to why the silicate-derived elements are rarely detected in the carbonates, which implies that their deposition was not contemporaneous with the carbonates. The absence of silica in the carbonates and absence of carbonate minerals in the siliciclastics may indicate that the limestones are clean of detrital material, and siliciclastics are also clean of carbonate inputs, which implies that there might be two different depositional systems in the upper Devonian to late Carboniferous time in the Paleotethys.

For instance, the concentrations of Mg and Sr can be used to infer the original mineralogical composition of carbonate rocks. The carbonates, which depicted high concentrations of Sr, are inferred to be aragonitic in origin, whereas carbonates, which have high concentration of Mg, are referred to be magnesian calcite in composition, which is a metastable carbonate mineral. These interpretations are related to the size of crystal lattice during a solid solution substitution process. The large unit cell of orthorhombic aragonite crystals can be accommodative to cations larger than Ca such as Sr, Na, Ba, and U, while the smaller unit cell of rhombohedral calcite preferentially incorporates smaller cations such as Mg, Fe, and Mn [55]. These criteria may help to infer the original mineralogy of the carbonates in Kinta Limestone as well. As the carbonates in the north contain a relatively lower Mg than the samples from the south of the Kinta Valley, it may indicate that the original carbonate sediments toward the south of the Kinta Valley were dominated by calcitic carbonates. The Sr concentration in the Kinta Limestone also showed a decreasing trend from north to the south of the valley. This may suggest that there were localized compositional variations during the deposition of the Kinta Limestone in the Paleo-Tethys. Sunagawa et al. [56] have demonstrated that the Sr is preferentially precipitated in aragonite and promotes the nucleation of metastable minerals. The Ca/Sr ratio for the Kinta Limestone also showed spatial variations from north (Kanthan) to the south (Kampar) as the Sr concentration decreased in a similar way. Thereby, this trend may have some relevance to the original mineralogical composition of the carbonates in the Paleo-Tethys too. The Ca/Sr ratio usually is a contribution from the aragonitic carbonates since calcite accommodates very little Sr. Thus, the ratio is important only with regard to warm environments, which are favorable to aragonitic organisms and the inorganic precipitation of aragonite. Therefore, the carbonates in the southern part of the Kinta Valley were calcite dominated, and the carbonates to the north might be aragonitic sediments during deposition.

The Ca/Mg ratios partly reflect temperature-depth-distance from shore and local ecological concentrations of aragonite-secreting algal taxa such as Halimeda [57]. The Kinta Limestone has depicted a systematic trend whereby the Mg concentrations increased toward the south of the Kinta Valley in the Kampar area. The elemental ratios for the selected samples also follow a spatial trend along the valley from north to south, and it may be related to temporal variation as well. If these variations represent the original signature of the Paleo-Tethys, it may contribute to define the depositional environment of the sedimentary and metasedimentary successions in the Kinta Valley. These results are consistent and fairly agreed with the work of Hutchison [58]. During the organic synthesis, magnesium and strontium are incorporated into solid solution of calcite and aragonite, respectively [59]. Gross Ca/Mg ratio of mixed detrital carbonate sediment could reflect temperature-depth-distance from the shoreline [57]. In the case of the Kinta Limestone, it might be possible to suggest that the deposition of the carbonates was not within a timeframe when the basin was getting a huge amount of detrital influxes. Therefore, there might be an episode of alternating depositional periods when the siliciclastic and the carbonates were deposited in a cyclic manner.

In some of the stratigraphic successions, there is a clear physical variation such as color, texture, sedimentary structural differences between strata. Such color differences often originate from variations in the incorporated transition metals during deposition and lithification. Other differences in color may also originate from variations in the organic carbon content of the rock. It now appears that the oceans during early Paleozoic and middle to late Cenozoic time favored precipitation of calcite, probably because of a lower ratio of magnesium to calcium during these times. The ratio of dolomite to calcite is much greater in ancient carbonate rocks than in modern carbonate sediments, presumably because $CaCO_3$ minerals exposed to magnesium-rich interstitial waters during burial and diagenesis were converted to dolomite by replacement [60]. The Kinta Limestone showed a slight difference with the general trend but showed local trends of increasing Mg from north to the south, which may be related to dolomitization or original mineralogy of the carbonates. Comparison in chemical characteristics of the Kinta Valley sedimentary successions in the timeframe of the upper Devonian-lower Carboniferous has shown measurable variations. The measured concentrations and ratios in the elements and oxides would imply that there is no homogenized lithofacies in the Kinta Valley rather the variations provide clues for the Kinta Limestone to improve our understanding on the stratigraphy. This is to convey that the idea of using the relict geochemical signatures of the Kinta Limestone could be a way forward to improve the stratigraphic correlation of the formation with local and/or regionally precisely dated stratotypes.

5. Conclusions

The preserved primary features and textural attributes of the described sections in the Kinta Limestone consistently implied a paleobathymetric variation from the present-day north to the present-day south of the Kinta Valley. It was revealed that the northern part of the Kinta Valley was dominated with sedimentary structures, which suggest deposition in a steeply dipping slope during the upper Devonian to lower Carboniferous time. The environment in the present-day north of the Kinta Valley was favorable for deposition of fine-grained sediments, which are common in low-energy depositional environments. The bedded chert in the Sungai Siput (N) may also suggest that it was a primary deposition of silica-rich material in a low-energy, relatively deeper environment. It is also clear that the depositional environment was above CCD but at considerable depth of water. The chemical stratigraphy of the Kinta Limestone has shown diagnostic characters that enable the establishment of chemical packages, which agreed with the biostratigraphic boundaries for the Kinta Limestone. The sedimentological and geochemical data sets suggest deposition in deep slope with low energy and probably anoxic condition. The various analyses combined with chemostratigraphy, an independent of type locality and stratotype, enable to interpret the depositional environment of the Kinta Limestone. Thus, it can be useful to relate other formations in or similar types of basins in the southeast Asia.

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Conflict of interest

There is no any conflict of interest to this chapter as far as the authors' knowledge during the submission.

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