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Comparison of stratigraphic situation and genesis of paleo soil bauxite-laterite basal horizon in Shemshak formation of Central Alborz, Sections (Glandrood - Lavij - Vaz)

Comparación de la situación estratigráfica y la génesis del horizonte basal de bauxita-laterítica del paleo-suelo en la Formación Shemshak de Alborz Central, secciones (Glandrood - Lavij - Vaz)

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Abstract

This study analyzes the geographic distribution of the Shemshak Formation in the Central Alborz, comparing stratigraphic sequences, lithology, tectonic influences, and depositional environments across the Glendrow, Lovej, and Vaz sections. The goal is to understand the sedimentary sequences and geological processes of the Triassic-Jurassic period. Sampling was carried out at key sections, with locations recorded via GPS. Mineralogical and petrological analyses were performed on 100 thin sections and polished samples using transmitted light microscopy and petrographic reflection. additionally, ten samples from the bauxite-laterite zone and ten from the base of the Shemshak Formation's laterite horizon were analyzed to identify climatological influences and tectonic events, using XRF and XRD at the Geological Organization of Iran, Binalud Mines. The presence of a bauxite-laterite horizon is crucial for reconstructing regional geology, with findings indicating that the Elika Formation underlies the Shemshak, deposited during the Early Cimmerian orogenic phase. The development of the Shemshak Formation occurred within a foreland basin transitioning into a back-arc basin, comprising diverse sedimentary rocks such as quartzite conglomerates, quartz arenites, sublitharenites, litharenites, mudstones, and claystones, often with coal interbeds. Palynological and paleosol data suggest a depositional environment from continental to coastal-deltaic. Tectonic and climatic influences, evidenced by discontinuities and east-west Glenrod faults, played a significant role in shaping the formation's sedimentary environment.

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Resumen

Este estudio analiza la distribución geográfica de la Formación Shemshak en el Alborz Central, comparando secuencias estratigráficas, litología, influencias tectónicas y ambientes depositacionales en las secciones de Glendrow, Lovej y Vaz. El objetivo es comprender las secuencias sedimentarias y los procesos geológicos del período Triásico-Jurásico. Se realizaron muestreos en secciones clave, cuyas ubicaciones fueron registradas mediante GPS. Se llevaron a cabo análisis mineralógicos y petrológicos en 100 secciones delgadas y muestras pulidas utilizando microscopía de luz transmitida y microscopía de reflexión petrográfica. Además, se analizaron diez muestras de la zona de bauxita-laterita y diez del horizonte laterítico en la base de la Formación Shemshak para identificar influencias climatológicas y eventos tectónicos, utilizando técnicas de FRX y DRX en la Organización Geológica de Irán, minas de Binalud. La presencia de un horizonte de bauxita-laterita es crucial para la reconstrucción de la geología regional, y los hallazgos indican que la Formación Elika subyace a la Formación Shemshak, depositada durante la fase orogénica Cimmeriana temprana. El desarrollo de la Formación Shemshak tuvo lugar en una cuenca de antepaís en transición hacia una cuenca de retroarco, compuesta por diversas rocas sedimentarias como conglomerados de cuarzo, cuarzarenitas, sublitarenitas, litarenitas, lutitas y arcillolitas, frecuentemente con intercalaciones de capas de carbón. Los datos palinológicos y de paleosuelos sugieren un ambiente depositacional que varía desde continental hasta deltaico costero. Las influencias tectónicas y climáticas, evidenciadas por discontinuidades y fallas orientadas este-oeste en Glendrow, desempeñaron un papel significativo en la configuración del ambiente sedimentario de la formación.

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Introduction

The upper Jurassic to the base of the Cretaceous period in the mid-Mesozoic era encompassing the final stages of the Early Cretaceous represents a critical interval marked by significant geodynamic transformations that influenced the broader Neotethyan realm[1-3]. Alongside metamorphic processes and pervasive deformation linked to the mid-Mesozoic Cimmerian geodynamic setting, tectonic features such as truncation-related structures evident in Triassic-Jurassic-Lower Cretaceous paleokarst carbonate breccias and lateritic deposits, including extensive bauxite layers serve as valuable markers of compressional tectonic activity, often associated with unconformities[4-9].

In Iran, the most important coal bearing horizon was located in the second geological period, and many studies have been conducted to trace the layers surrounding it. Iran's coal reserves are located in the Shemshak Formation, which is scattered in most parts of Iran except for the Zagros. One of the most important coal-bearing deposits is located in the Alborz zone. The geology of the Alborz region is the subject of study and research by many researchers and thinkers who, along with other parts of the world, are investigating its events. The central Alborz, especially the Glendrood zone, is difficult to pass due to its vegetation and is highly tectonized in terms of structure. Accurate geological studies seem almost impossible without examining tectonic and stratigraphic processes. In general, stratigraphic studies discuss various geological events such as biological evolution and the transformation of various rocks, sedimentary strata, tectonic factors, and sedimentary environments.

The formation and distribution of bauxite and laterite horizons are important indicators of paleo-weathering conditions and tectonic evolution, especially in orogenic and tectonically active regions such as the Central Alborz. Geological research, despite its extensive and dynamic nature, is not without flaws. In recent centuries, particularly after the Industrial Revolution, the search for energy resources has brought significant attention to the vast coal reserves worldwide. In Iran, the most important coal bearing horizons are from the Mesozoic era, with extensive studies conducted to explore these layers. Iran's coal reserves are primarily located within the Shemshak Formation, which is scattered throughout the country except for the Zagros region. One of the key coal-bearing deposits is situated in the Alborz zone, an area of great interest to geologists due to its rich geological history and complex tectonic structure. In the Central Alborz, the Shemshak Formation is a key segment recording Late Triassic to Jurassic sedimentation, with basal horizons frequently containing paleo soil and bauxite-rich layers[10].

In this study, the Shemshak Formation in the Glendrood region is examined in terms of the sequence of sedimentary layers, lithology, tectonic processes effective in the formation of this formation, and the sedimentary environment. The Shemshak Formation in the Alborz region is also very important in terms of recording historical geological issues, including plant and animal biological events and analyzing past climate. On the other hand, the increasing human need for energy, especially fossil fuels, has led to this formation receiving special attention as it contains the largest coal reserve in Alborz. Therefore, The study of studies the lithostratigraphy and sedimentary environment of the Shemshak Formation in the central Alborz region of Glendrood.

The study area is located in northern Iran, within Mazandaran province, the Alborz Mountains, running east-west across northern Iran, pass through this province. Mount Damavand, the highest peak of the Alborz, is located in southern Mazandaran. The Alborz range is divided into western, central, and eastern sections. The central part, known for its geological and geographical features, corresponds to the U-shaped part of the Caspian Sea and extends from coastal sediments to the heights of central Alborz. This study will focus on the coal-bearing sediments between Haraz Valley and Chalus River, specifically the Glendrood area, with detailed examination of the Shemshak Formation in three sections: Glendrood, Lavij, and Vaz.

Materials and methods

The research was carried out in the Alborz region, focusing on its geological formations and sedimentary stratigraphy. The study period extended from March 2023 to August 2023. Field investigations were conducted at several key locations within the Alborz range, specifically in Glendrood, Akrasar, Lahband, Claris, and Jowhar-deh.

Fieldwork and Sampling. Fieldwork involved systematic sampling at sites selected based on their geological significance and representation of diverse sedimentary units, aligning with methodologies employed in stratigraphic rock and sediment analyses[11]. At each location Glendrood, Akrasar, Lahband, Claris, and Jowhar-deh core samples, sediment, and rock specimens were collected to capture the variability in geological conditions[12]. The sampling procedure adhered to established protocols ensuring representative geological coverage.

X-ray fluorescence (XRF). To measure the oxide levels of essential elements, present in black sand, pressed sample tablets were examined using a Rigaku Supermini200 wavelength-dispersive X-ray fluorescence spectrometer, operating at 50 kV and 200 W with a Pd anode. The instrument is equipped with detectors for both light elements (using a gas flow proportional counter) and heavy elements (via a scintillation detector), and employs a selection of analyzing crystals LIF 200, PET, and RX25 chosen according to the specific elemental range under investigation. The quantification process was carried out using the Rigaku Profile Fitting-Spectra Quant X (RPF-SQX) software, which allows for standardless analysis based on theoretical models combined with precise calibration of the instrument)[12,13].

X-ray diffraction (XRD). X-ray diffraction (XRD) measurements were carried out at the Faculty of Science, Physics Department, Assiut University, Egypt. A Philips PW 2103 diffractometer (Netherlands) was used for the analysis, operating with CuKα radiation produced by an X-ray tube at 35 kV and 20 mA. Data were collected across a 2θ range of 4° to 80°, (with a step size of 0.06°)[12,14,15].

Sample preparation and laboratory analysis

Petrographic analysis. Thin sections prepared from rock samples were examined under polarized light microscopy to identify mineral components and sedimentary structures, following standard procedures outlined by Sujatono[16].

Geochemical analysis. Trace element concentrations and sulfur content were quantified using ICP-MS and XRF techniques, as recommended by Jochum et al.[17] for geochemical characterization.

Paleobotanical and Palynological analysis. Sediment samples underwent processing to extract plant fossils, spores, and pollen, which were analyzed under light microscopy for paleoecological reconstruction, in accordance with methods described by Feurdean[18].

Assessment methods

Statistical analysis. Descriptive statistics: mean, median, and standard deviation were calculated for geochemical and paleobotanical data to summarize the characteristics of the samples.

Comparative analysis. ANOVA (analysis of variance) was used to compare differences in mineralogical and geochemical properties across different sedimentary units.

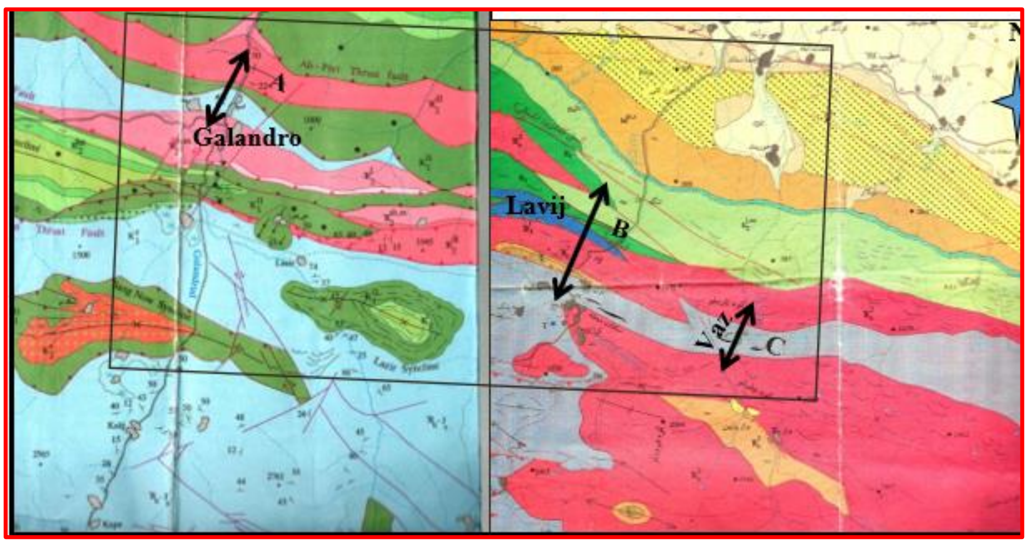
Correlation analysis. Pearson or Spearman correlation coefficients were calculated to assess relationships between variables, such as sulfur content and pyrite formation.

Software. Data were analyzed using statistical software packages such as SPSS (Statistical Package for the Social Sciences) or R for performing statistical tests and generating visual representations of the data.

This methodology was designed to provide a thorough understanding of the geological and paleobotanical features of the Alborz region, offering insights into sedimentary processes and past environmental conditions[19].

Sampling procedure. Systematic sampling was employed to ensure comprehensive coverage of different sedimentary layers and formations. Core samples, sediment samples, and rock specimens were collected from each site to represent the range of geological conditions present[20]. (Figure 1).

Figure 1 Location of the study area



Sample preparation and analysis

Petrographic analysis. Rock samples were prepared as thin sections and examined under a polarized light microscope to determine mineral composition and sedimentary structures.

Geochemical analysis. Trace elements and sulfur content were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) and X-ray fluorescence (XRF) techniques.

Paleobotanical and Palynological analysis. Sediment samples were processed to extract plant fossils, spores, and pollen. These were analyzed using light microscopy to infer past vegetation and climatic conditions.

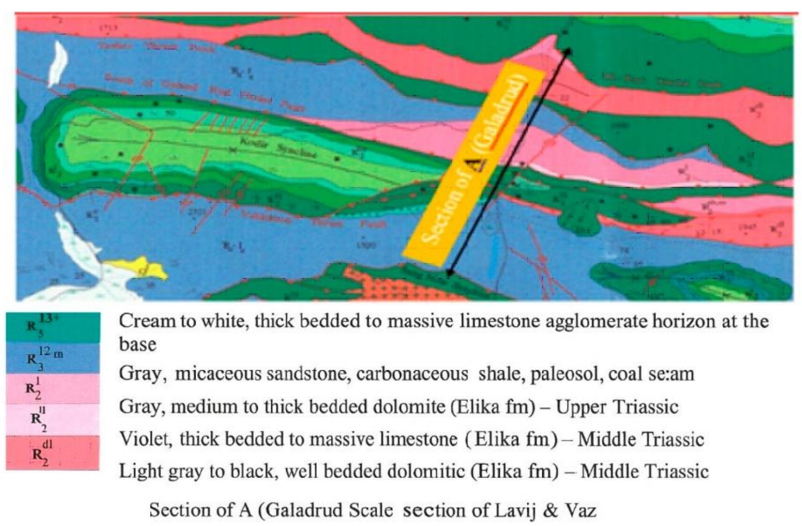
Study variables. Independent variables i) Geological formations (e.g., Jowhar-deh conglomerates, Akrasar section), stratigraphic layers, and sediment types. ii) Dependent variables. Mineralogical composition, sulfur content, plant fossil presence, and palynomorph types.

Results

In terms of paleogeography, coal bearing sediments have been spread over the vast areas of the globe in the past. These sediments indicate epeirogenesis and vegetation periods in terms of origin, and numerous studies have been conducted on such sediments. Due to complex tectonics and dense vegetation, necessary to conduct detailed geographical studies in Central Alborz to reveal the formation mechanism, tectonic events, and its climatology. The thickness of the lower member of the Elika Formation in these sections ranges from 95 m in the type section to 195 m in the Veresk section. This member mainly consists of heavily bioturbated thin to thick-bedded limestone and shale intercalations which deposited under fair-weather and storm conditions. Four stratigraphic sections in the Alborz Mountains of northern Iran were selected. Field and microscopic studies indicate that the intra formational flat pebble conglomerates were deposited by powerful storm generated flows in open marine, shoal, lagoon and tidal flat beach ridge sub-environments related to carbonate homoclinal ramp platforms[21].

According to field observations, in terms of lithostratigraphy, there is a thick sequence of geological strata in the studied sections with diverse lithology and complex tectonics. The complete disappearance of Elika formation (Lower-Middle Triassic) and the placement of brachiopod limestone shales of Nesen Formation (Upper Permian) next to Shemshak formation (Lias) in Lavij section and the laterite horizon in the Shemshak base (Glandrood section) indicate important tectonic events (Figure 2).

Figure 2 Geologycal map of Baladeh Scale 1:25000, section of Galadrood

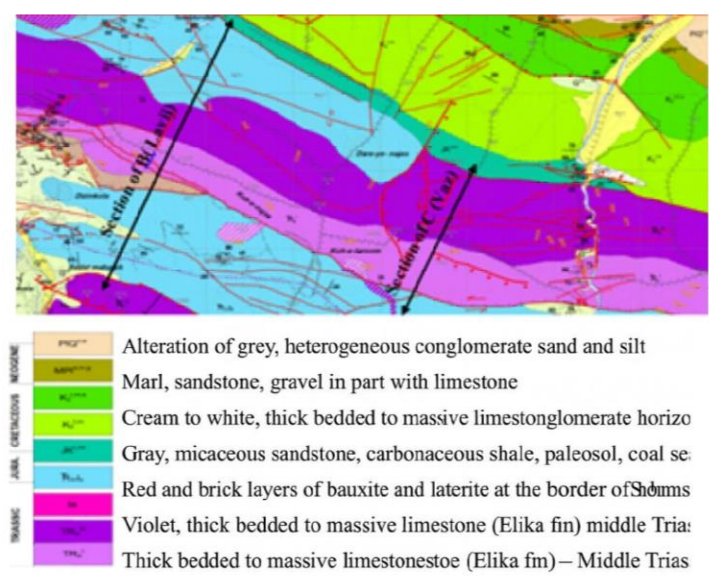


On the other hand, petrography studies show the existence of low-grade metamorphic rocks, high quartz bearing sedimentary rocks, and small amounts of volcanic rocks before the formation of the Shemshak formation base horizon in the region. Shemshak group is divided into four sections: Lalehband (Triassic), Ekraser, Kalariz, and Javaherdeh with lower to middle Jurassic age Rhaetian-Hettangian[22]. Mineralogical, there exists 13 minerals along with bauxite-laurite deposits including gibbsite, Boehmite, diaspore, anatase, rutile, hematite, goethite, corundum, kaolinite, halloysite, and quartz. Following the early Cimmerian orogenic event, the detrital deposits of Shemshak group were formed in a continental marine basin with Middle-Late Triassic to Lower Bajocian age[21,23].

Along the SE Alborz Mountains in northern Iran, thrust loading seems to have been accompanied by post-Eocene transversal left-lateral faulting during the late Cenozoic. Here, the range-front north Semnan fault has played a major role in the thrust loading and the development of the foreland basin. This fault has placed the Cenozoic succession upon the foreland basin from the early Miocene to the present[24].

The Shemshak group sediments in northern Alborz have been deposited along the Elika carbonate formation without any sedimentation interruption and stop[25]. The upper Triassic and lower upper Jurassic detrital deposits belong to the foreland basin[26]. The stratigraphy of the foreland basin is the result of interaction between three processes: overthrust crustal deformation, deposition, and erosion[27]. Subsidence in the foreland basin mostly indicates tectonic factors and the filling of the basin by erosional sediments[28]. The foreland basin was formed in two stages: the fast subsidence stage in which the basin was filled with asymmetric and proximal sediments, and the uplift stage in which the weathered sediments were formed as a result of land erosion[29]. The presence of melaphyres at the base of Shemshak formation deposits indicate a tension phase after the middle Triassic compressional phase[30]. The petrography of the melaphyric part of Shemshak base in Alborz indicates alkaline magma in an intracontinental tectonic setting[31]. Moreover, the presence of iron and aluminum oxides, regardless of the parent rock, can be influenced by the weather conditions of the sedimentary basin at the time of formation. The bauxite horizon with the surrounding layers is completely conformable with similar in-situ sedimentary characteristics (Figure 3).

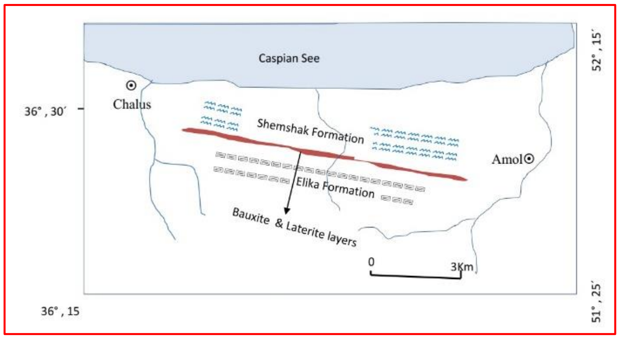
Figure 3 Geologycal map of Lavij Scale 1:25000, section of Laviv & Vaz



Geological map of Lavij Scale 1:25,000, section of Lavij & Vaz

Field studies show the existence of a bauxite laterite deposit at the boundary of Elika and Shemshak formations across the northern central Alborz (Glandrood). However, regions where, in terms of lithostratigraphy, top limestones of Elika formation were not influenced by tectonic events and the lower sandstones of coal-bearing Shemshak formation is located can be investigated. In Shemshak formation divisions, the bauxite-laterite horizon is informally called Parvar Section[32] (Figure 4).

Figure 4 Map of the location of bauxite layers between Haraz valley and Chalus



Within the northern structural-facies zone, the Parvar section is characterized by the presence of reddish-brown bauxites, gray flint clays, and, less commonly, colored kaolinitic clays. In the Deh-e-Akrasar area, the thickness of the colored bauxite layer reaches approximately 9 m, whereas in the Qeshlaq area, a kaolinitic clay layer associated with the Parvar section has been identified with a thickness of only 80 cm.

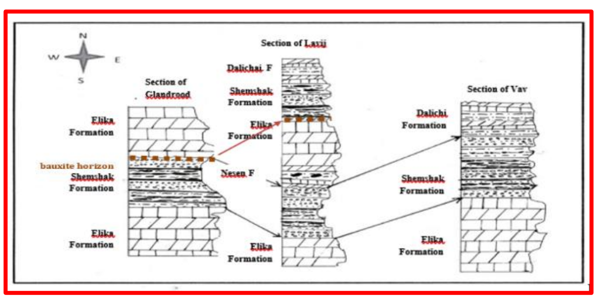
In terms of stratigraphy, the footwall of this horizon is located on the top limestones of Elika formation (alternative marl and limestone layers). The structure of bauxite layers is so that there exists pisolitic bauxite layers from the bottom along with intercalations of smoky to bright silica, followed by 6 m thick bauxite layers and brick red fine-grained sandstone in the upper part of Shemshak formation (Ekraser). This bauxite horizon in other Alborz regions is known as Jaban basalts[26], iron-bearing nodules[30], and gypsum melaphyric part[23]. For this reason, some researchers such as Nabavi believe in the nonconformable origin of bauxite and laterite.

In terms of geochemistry, the analyses and elements in the bauxite laterite deposit indicate the sedimentary environment and the formation conditions of the sedimentary basin. Tectonically, the sedimentary basin had been out of water by the compressional movement of the early Cimmerian orogenic phase. According to the above discussions, the genesis of bauxite and laterite can be investigated from two aspects. Regardless of the dolomitic limestone foundation of Elika formation in Upper Triassic, sedimentary stagnation and weather conditions are the main factors in forming this horizon. The presence of iron-bearing (sometimes fossil-bearing) concretions next to clay and aluminum layers indicate peneplain bauxite, showing the exit from water and shallow marine-fluvial, and lagoonal conditions.

The chemical analysis of this bauxite laterite horizon shows that the titanium and iron levels were 2 and 14 %, respectively. The origin of these elements can be attributed to the rocks in older formations (Permian-Triassic) or basic igneous deposits in relation to the tension phase after the compressional phase of early Cimmerian orogenyesis. The Cimmerian event in northern Iran is the result of continental crust collision which was accompanied by regional discontinuities and severe sedimentation variations. Regarding the tectonic setting of bauxite and laterite in the region, it should be noted that the transition from Paleozoic to Mesozoic across Iran was accompanied by relative tectonic relaxation. After a short sedimentary stagnation (sometimes at shortest time), Paleozoic platform conditions continued until the beginning of late Triassic. Stratigraphically, the transition from the brachiopod shales of Nesen formation to thin (vermiculate) limestones of Elika formation was completely conformable without any sign of discontinuity.

It seems that this boundary should be further studied in terms of biostratigraphy (paleontology) to confirm continuous sedimentation in Permian Triassic in Glandrood section[33]. However, important tectonic movements such as upper Triassic or early Cimmerian occurred from late Triassic to the end of the Cretaceous. According to most geologists including Aghanabati et al.[26], in the northern slope of central Alborz (Glandrood), the transition from limestones and dolomites in Elika formation (carbonate cycle) to detrital and coal-bearing sediments of Shemshak formation occurred gradually[25]. However, Jenny & Stampfli[34] believes that the Cimmerian phase in the study area includes epirogenic phase and exit from water. In general, the outcome of early Cimmerian phase in Alborz is changing the conditions and type of the sedimentary basin, geodynamic variations and the location of plates such as the convergence of Iran and Turan plates and the formation of an up life in Iran[35].

Figure 5 Correlated of sections A, B, C



Studies at Glandrood valley, Vaz, and Lavij, particularly at the mouth of Lavij River (200 m north of Haramo waterfall) and Glandrood valley (Kodir pass) show that the average thickness of bauxite and laterite layers is 5-6 m. This bauxite horizon extends as N70W with a slope of N45NW to north and northwest. These layers have been traced for 25 km, remained buried under limestone deposits at the boundary of Elika and Shemshak formations in some points. The above residual deposits prove that simultaneous with early Cimmerian orogenic phase in Glandrood, there has been exit from water, and the bauxite horizon with conformable footwall and hanging wall expresses the discontinuity of the disconformity type. (Figure 5)

It can be concluded that the bauxite-laterite horizon is a result an uplift stage as up dip bloke (as horst graben) and resulting epeirogenesis. In Glandrood, Akrasar section is located in sections where the bauxite laterite is not affected by tectonic events (Lavij section). This section has a thickness of 150 m and its lithology consists of fine-grained sandstone layers containing plants, claystone, and siltstone along with iron-bearing nodules (Figure 6).

Figure 6 Ferruginous xylem in the fine-grained sandstone of the lower part of Shemshak formation

Regardless of the origin and genesis, this residual horizon shows exit from water as a result of the above event.

In the study area, samples were taken from the bauxite outcrop in Lavij valley and Glandrood. In terms of lithostratigraphy, this horizon is located on the dolomitic lime surface of Elika formation, followed by pissolitic bauxite containing smoky to bright silica intercalations, diaspore, and clay minerals such as kaolinite and iron oxides. Non-clastic silica sediments are divided into primary, secondary, and organic deposits[36]. Non-clastic silica sediments are located as silica nodules at the lowest part of the bauxite horizon section, probably formed as silica gels, deposited with increasing weight. Kaolinite can be formed late or in situ. In-situ kaolinites have been formed by kaolinitation of bauxites and other clay minerals. Titanium oxide (TiO_2) is observed as anatase and rutile minerals in different parts of the section, but brookite is rarely observed. Anatase formation can be related to the breakage of ilmenite or augite[37]. Brick red fine-grained sandstones of Shemshak formation (Akrasar) are located on the hanging wall. Iron oxides mostly exist as goethite, causing a brick red color.

Rocks with steep slopes increase the flow of surface runoffs, preventing the concentration of residual deposits. Older igneous masses were not observed in the study area, and only the melaphyric part can be proven. Climatological characteristics are the most important conditions for the formation of bauxite reserves. The presence of rainy periods with rainfall stops and hot and dry conditions, and the repetition of these conditions in a limited geological period had a key role in breaking silicates and the release of harmful minerals including silica. A precipitation rate over 1200 mm under tropical and subtropical conditions is among such conditions[38]. Such conditions existed in upper Triassic in northern Alborz (Glandrood), forming the bauxite–laterite horizon on Elika formation, located as a stratiform deposit between the Elika and Shemshak formations.

From to the top to bottom, this deposit is formed of four parts: lower kaolinite, shale bauxite, hard bauxite and upper kaolinite. The presence of palynological elements such as the spores of acritacs and fungi, preserved plant trunks in sandstones, and coal layers in Lavij Anarestan Coal Mine (east of Glandrood) indicate a continental to coastal-deltaic environment. In addition, the diversity of ferns and lithophytes indicate hot and humid weather conditions[33].

Gentle topography with alternating low-height elevations (unlike steep slopes) and the controlled permeability on the top of groundwater tables play a key role in chemical weathering. As a result of accumulating copper-bearing sediments on the karst lime surface and their surface depressions, the bauxite–laterite deposit is formed, and rare earth elements (REE) are concentrated due to clay adsorption[39]. The above factors provide sufficient time for filtering dissolved silica and iron and depositing Al_2O_3 in rainy periods. In contrast, severe surface currents cause the erosion of sediments formed by weathering on steep topographical slopes. The stability of deposit residues is of great importance for the formation of an economic bauxite reserve. Thick layers containing Al_2O_3 can be rapidly accumulated under proper, ideal conditions. On the surface of the lime-dolomite of the Elika Formation and its immediate surroundings, there are pizzolite bauxite containing smoky to light-colored silica intercalations, then boehmite and diaspore, and finally clay layers, and then on the upper side, brick-red (fine-grained) sandstones of the Shemshak Formation. And iron oxides are mostly in the form of goethite, whose fractionation caused the bauxites of this area to be known as bauxite and laterite.

The average percentage of main oxides obtained from analyzing the bauxite laterite sample is as Table 1. Table 2 compares ten bauxite laterite samples in terms of iron and titanium content. (Tables 1, 2)

In central Alborz, the exit of water was not stable for a long time in the study area (Glandrood), and the bauxite–laterite deposit was formed with a diasporic mineralogical composition along with silica and iron and titanium oxides, indicating epirogenesis during middle Triassic to early upper Triassic and the dominance of tropical climates in this region, causing the formation of bauxite as in many other regions around the world. The geological conditions of dynamic sedimentary basin had not been provided for the formation of a large reserve. As a result, 5-6 m bauxite laterite had been deposited, and detrital conditions dominated and lower sandstone sediments of Shemshak formation (Akrasar) had been formed. The above-mentioned horizon with surrounding layers is completely conformable and is a part of the sedimentary sequence (Figure 7).

Table 1 Average percentage of oxides in the Bauxite Laterite Sample

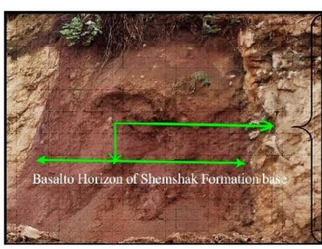
Oxide type	Al_2O_3	Fe_3O_4	SiO_2	CaO	MgO
Percent	17.4	14	43.62	5.37	4.032

Table 2 Average percentage of elements in the Bauxite Laterite Samples

No	1	2	3	4	5	6	7	8	9	10
Fe %	11.02	10.87	15.4	8.3	7.34	20	14	15.2	11.6	14.22
Ti %	1.81	1.74	2.3	3	2.5	1.7	1.75	0.570	1.8	1.71

At the end of Triassic, due to the early Cimmerian orogenic phase and the crust collision and bending, the carbonate environment of Elika formation was changed to clastic coal-bearing sediments, and the Shemshak formation was deposited in the foreland basin.

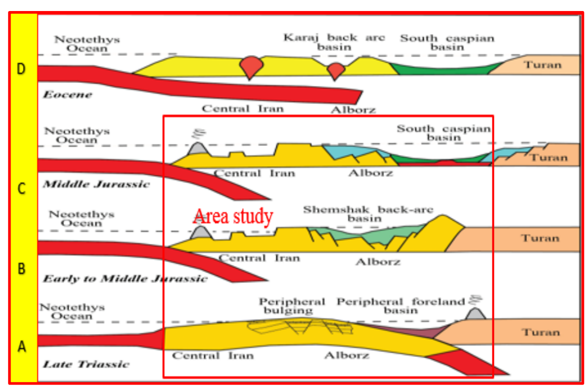
Figure 7 Analysis of two samples of Bauxite laterite of the Base of Shemshak Formation by XRF method



S.N.	1	2
L.N.	203	204
formula	(%)	(%)
SiO_2	45.39	49.42
Al_2O_3	12.90	14.22
Fe_2O_3	10.87	4.42
K_2O	4.42	4.40
MgO	5.32	3.31
P_2O_5	0.19	0.20
MnO	0.11	1.71
L.O.I.	15.52	12.70

They formed from Neoprotrozoic to recent time as the results of the relative plate motion in south west of Asia in Tethyan realm (Figure 8). The basins include: Prototethys late neo-Proterozoic to early Ordovician epi-continental/platform basin[40], Paleotethys Middle Ordovician Triassic to lower Jurassic foreland basin[41], Shemshak back arc rift basin[21], South Caspian carbonate platform basin[22], Paleocene clastic sedimentary basin[23], Karaj back arc basin[24], Oligo-Miocene foreland basin[25], Pliocene-Pleistocene intramontane basin[26,42].

Figure 8 Tectonosedimentary basin in central Alborz from late Triassic to Eocene Times[21]



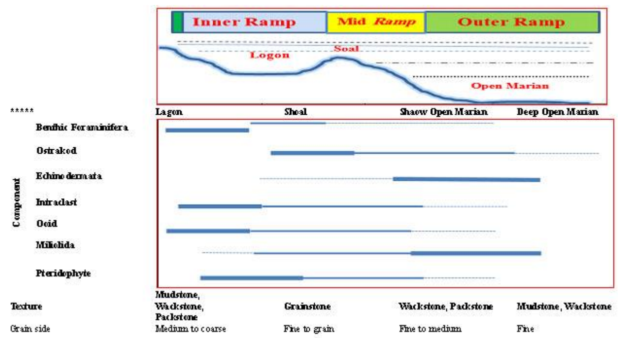
According to the above model, due to the compressional phase of epirogenesis, the laterite section of Shemshak formation base was formed under tropical weather conditions, followed by the formation of the lower sandstones of Shemshak formation due to deepening of the basin by subsidence of sediments (felsic). In the next stages, with decreasing the depth, vegetation and the coal-bearing section were formed.

The sequence of coal-bearing sediments continued up to middle Cimmerian phase, followed by deposition of Dalichai formation sediments. In Section A, the lower sandstones of Shemshak formation are conformable on the laterite section, followed by lower coal-bearing layers. The thickness of different parts of Shemshak formation in Section A is 850 m. In the northern part of Section B, the Shemshak base is located conformably on the laterite horizon, followed by underlying sandstones and lower coal–bearing layers, located unconformable next to Dalichai formation, and the upper parts of Shemshak have been disappeared due to the tectonic action. In the south of the same section, the lower and upper borders of Shemshak formation are faulty and unconformable. The lower sandstones are pushed on Elika formation and upper sandstones on the Nesen formation (sandy limestones and brachiopod shale), and coal-bearing sediments are not observed due to faulting. The Shemshak thickness in this section is 800 m. In Section C, the thickness of Shemshak formation is 650-700 m, and the bauxite horizon, the sandstone, and the lower coal-bearing sediments have been removed. The sandstone at the upper part of Shemshak in this section ends conformably to Dalichai limestones[43]. According to experimental studies and field geological evidence, the sedimentary environment for the sandstone parts of Shemshak formation is coastal to fluvial shallow environment and is of karst type for coal-bearing palustrine parts and the bauxite–laterite horizon. Based on the plant fossil, Shemshak formation age is from Rhaetian to Bajocian (Table 3).

Discussion

The Parvar section's lithological features including reddish-brown bauxites, gray flint clays, and occasional kaolinitic clays suggest a well-developed weathering profile formed under humid tropical to subtropical conditions. Our observations, highlighting a significant thickness contrast (~9 m of bauxite in Deh-e-Akrasar vs. mere 0.8 m of kaolinitic clay in Qeshlaq), reflect substantial lateral variability influenced by paleotopography, drainage, and sediment supply.

Table 3 Lateral distribution of microfacies and components of the Shemshak formation in the studied sections



Geochemical and petrographic analyses of karstic bauxite horizons in the Alborz zone, such as those at Gheshlagh, Siahrudbar, and Separdeh, reveal mineral assemblages (kaolinite, boehmite, diaspore, goethite, hematite, anatase, rutile) and texture types (pelitomorphic, pisolitic, ooidic, fluidal) akin to the Parvar section[44]. These studies affirm that the bauxites formed in situ atop karstified carbonate host units, under humid conditions and within stable tectonic frameworks.

The thick bauxite layer in Deh-e-Akrasar mirrors extensive laterization developed in flat or structurally stable areas, allowing deep weathering of aluminosilicate rocks into bauxite. Conversely, the thinner kaolinite layer at Qeshlaq suggests more dynamic conditions either increased erosion, shorter exposure time, or truncation by early burial or tectonism.

A comprehensive geochemical study by Abasaghi et al.[45] across the eastern and central Alborz shows that lateritic–bauxitic horizons formed during the Permian Triassic boundary displays high Al_2O_3 (up to ~31.5 %) and Fe_2O_3 (~37.9 %) contents, with mineral associations including diaspore, boehmite, hematite, anatase, and kaolinite[45] further corroborating our field observations in the Parvar section.

Comparison with the Gheshlagh deposit (20 m thick stratiform layer) highlights a vertically zoned profile: an upper boehmitic-hematitic unit, central hard bauxite, and lower kaolinite-rich zone[46]. This zonation parallels the Parvar sequence, particularly in Deh-e-Akrasar, reinforcing the model of depositional architecture driven by supergene weathering atop carbonate platforms. Global analogues such as Yakshawa (NW Iran) and Mediterranean-type bauxites echo this vertical stacking of clay-rich horizons, pisolitic structures, nodular textures, often underlined by karstic infiltration and intermittent groundwater flow in a humid tectonic regime.

Studies of trace and rare earth element (REE) geochemistry in Iranian bauxites (e.g., Biglar, Pirashkaft) document consistent enrichments in Al, Ti, Zr, Nb, Hf, Ga, U, Th, V, and Cr, while elements like Si and Ba tend to deplete[47]. This aligns with geochemical trends noted in the Alborz bauxites positive Ce anomalies, LREE/HREE fractionation, and underlying tropical weathering signatures. Therefore, it's plausible that the Parvar bauxites also contain elevated REE and titanium minerals, particularly anatase and rutile, hinting at both economic and geochemical significance.

i) Paleoclimatic and Environmental Insights. This study is crucial for understanding the paleoclimatic conditions of northern Iran during the late Triassic to early Jurassic periods. The presence of bauxite and laterite deposits formed under tropical to subtropical conditions reveals significant climatic information. Bauxite formation requires intense weathering under warm and humid conditions, while laterite forms in alternating wet and dry periods[48]. These conditions indicate a shift from carbonate to clastic sedimentation, reflecting broader climatic changes. Such insights help reconstruct past environments and provide context for the climatic evolution of the Tethyan realm, offering parallels to similar global deposits. ii) Tectonic and Sedimentary Basin Dynamics. The study highlights the role of significant tectonic events, particularly the early Cimmerian orogeny, in shaping the sedimentary record of the Central Alborz Mountains. The transition from the Elika carbonate formation to the clastic Shemshak sediments underscores how tectonic forces influenced sedimentation and basin development[26,49]. Understanding these tectonic processes is crucial for reconstructing the history of the region's foreland basins and provides a framework for interpreting sedimentary sequences in other tectonically active regions. iii) Economic and resource implications.

The research has important implications for the economic geology of the region. Bauxite and laterite are economically significant as primary sources of aluminum and other minerals. By elucidating the formation processes and conditions of these deposits, the study aids in evaluating their resource potential and informs exploration strategies[50]. This contributes to better resource management and highlights the region's potential for future mining endeavors. iv) Integration with Broader Geological Models. The findings contribute to global geological models by providing detailed data on sedimentary sequences and tectonic activity. The integration of field observations, mineralogical, and geochemical data helps refine models of basin evolution and tectonic interactions in the Tethyan realm[51]. This research not only enhances our understanding of local geological processes but also informs broader discussions on plate tectonics and sedimentary basin development.

In summary, this research provides critical insights into the paleoclimatic conditions, tectonic influences, and economic potential of the bauxite laterite horizon in the Central Alborz Mountains. It enriches our understanding of ancient sedimentary environments, supports economic resource exploration, and contributes to global geological models.

The following results were obtained from geological studies. i) Regarding the geological age, the oldest and youngest geological settings are Nesen formation (brachiopod shales) and fluvial sediments of the current age, respectively. ii) The lower boundary of Shemshak formation in the study area (bauxite-laterite) lacks fossils and is located on the upper part of Elika formation with the age of middle Triassic based on the stratigraphical position. iii) After the residual laterite deposit (Parvar district), detrital facies of Allah Band and Akrasar are located. Based on statistical studies on palynomorphs, they have a middle Norian age. At the end of Norian, the sea began to regress, remaining deltaic fluvial-lagoonal deposits at Rhaetian in Kalariz (coal-bearing sediments). iv) Regarding the lithostratigraphy of studied sections, Lavij (northern and southern sides of Sordar) contains the most complete sedimentary layers of the second period (Permian Triassic border), Elika formation (Triassic), bauxite laterite horizon of Shemshak base, Shemshak formation (lower-middle Jurassic), and Dalichai formation (upper Jurassic). v) Critical lithological changes had occurred across the Shemshak formation. The rocks in the study area include siliceous conglomerate (containing pyrite in some regions), muscovite sandstone (quartz arenite, sublithic arenite), buffy sandstones, claystone, siltstone, shale, marl (locally), coal lenses and layers, and siliceous lenses. vi) Tectonically, early and middle Cimmerian orogenic phases had influenced the study area. As a result of compressional force from early Cimmerian event in upper Triassic, the marine basin of carbonate Elika formation had been converted to the detrital environment of Shemshak formation by the regress of sea and complete stagnation of sedimentation (Parvar laterite section). At the upper boundary of Shemshak formation, the sedimentary basin has been deepened as a result of middle Cimmerian phase, remaining the shale–lime sediments of Dalichai formation. Therefore, Shemshak formation is located between these two important tectonic events. vii) Field evidence shows the origin of carbonate residual deposits and coal-bearing detrital sediments of Triassic Jurassic in central Albroz, which have been deposited in the foreland basin. At the end of Triassic, under the influence of early Cimmerian orogenic phase, the sedimentary basin was removed from water due to the compressional force (laterites of Shemshak base), and erosion remained detrital sediments of Shemshak formation in a shallow environment. Thereafter, the sedimentary environment was turned into a fluvial-palustrine environment, leading to vegetation and coal-bearing deposits (Kalariz). viii) The study results show that the sedimentary environment of carbonate rocks (lime-dolomite) of Elika formation (lower border) had been deposited in a deep to semi deep sea. The residual bauxite laterite horizon had been deposited in tropical weather conditions, and the lower sandstone part of Shemshak formation had been deposited in a shallow marine environment. Moreover, the coal-bearing section had been deposited in a deltaic fluvial palustrine environment, while lime marl of Dalichai formation had been deposited in a deep marine environment. ix) In Glandrood section (A), the lower sandstones of Shemshak formation are located conformably on the laterite part, followed by lower coal bearing layers. The thickness of different parts of the bauxite laterite horizon is this section is 9 m with a horizontal distance of nearly 13 km from Section B. x) In the north of Lavij section (B), the Shemshak base is conformably located on the bauxite-laterite layers, followed by lower sand stones and coal-bearing layers. Therefore, other upper parts of Shemshak had been disappeared due to tectonic action. In the southern part of the same section, the lower sequence of Shemshak formation is faulting and unconformable. The lower sandstones had been pushed on the Elika formation, while upper sandstones had been pushed on the Nesen formation (sandy limestones and brachiopod shales) without any sign of the bauxite laterite horizon. The thickness of the bauxite horizon in Section B (Lavij) is 6 m. xi) In Section C (Vaz), the thickness of Shemshak formation varies from 650 to 700 m, and the bauxite horizon and the sandstone and lower coal-bearing sediments had been removed. This section is 7 km away from Section B. Sandstones in upper part of Shemshak in this section conformably end to Dalichai limestones. xii) In Lavij Section (B), in the sequence of Shemshak and Elika layers in the northern part of the section in Lavij Road, the base of Shemshak formation is located conformably on the bauxite–laterite horizon, followed by the lower sandstones of Shemshak. In the southern part of Section B (Lavij hot water springs), with the repetition of Shemshak layers as a result of early Cimmerian orogenic phase, the Shemshak Formation has been pushed onto the Nesen formation (sandy limestone and shale containing abundant brachiopods).

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Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Ethical considerations

Since the research involved geological sampling without human subjects, no ethical approval was required. Permissions for sampling activities were obtained from relevant local authorities and landowners, following regulations advised by policy frameworks for geological surveys[52].

Research limitations

The main limitations of the study were related to limited accessibility in certain parts of the outcrops due to terrain and weather conditions. Geochemical data acquisition was also restricted by sampling constraints in remote areas.

Authors' contributions

All authors contributed equally to the conceptualization, field investigations, stratigraphic analysis, data interpretation, manuscript writing, and final approval of the article.

Data availability

The data supporting the findings of this study are not publicly available due to their technical specificity and field-sensitive nature, but they are available from the corresponding author upon reasonable academic request and for non-commercial research purposes.

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All authors have reviewed and approved the final version of the manuscript and consent to its publication.

Use of artificial intelligence in writing

No generative artificial intelligence tools were used in the writing of this manuscript. All content was produced by the authors.

Image generation disclosure

All figures, illustrations, and diagrams in this article were generated by the authors using standard geological and graphical software. No AI-based tools were used for image creation.

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