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Engineering-Geological Characterization of a Periclinal Closure for Open-Pit Slope Design: the Oum El Khecheb Phosphate Mine, Gafsa–Metlaoui Basin, Tunisia

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Open-pit slope design in structurally controlled stratiform deposits depends on an engineering-geological model that resolves bedding geometry, the position of weak interbeds and the distribution of overburden. This paper presents such a model for the eastern periclinal closure of the Oum El Khecheb phosphate mine, in the Gafsa–Metlaoui basin of south-western Tunisia, a sector where the pit face approaches its natural structural limit and which had not previously been documented systematically. Lithostratigraphic logging, structural mapping, bench-face observation, digital terrain modelling and statistical analysis of thirteen trench and borehole sections were integrated into a three-dimensional model. The eastward attenuation of the Oum El Khecheb anticline generates a perched dissymmetric syncline: bedding dip decreases from 30°–45° on the northern flank to 10°–25° near the anticlinal crest, and the fold axis plunges about 25° eastward. The phosphate horizon has a mean thickness of 12.10 m (standard deviation 1.91 m; coefficient of variation 15.8%; range 8.60–14.82 m), decreasing from 14.28 m above the structural crest to 10.85 m on the southern flank. No major fault interrupts its continuity across the closure, whereas persistent marly interbeds are identified as potential weak layers on lithological and geometric grounds. Because bedding strike rotates through the periclinal nose, the angle between bedding and the excavated face changes from one bench orientation to the next. The model therefore defines the geometric framework for slope design and identifies where oriented sampling, strength testing and kinematic analysis should be concentrated before slope angles are finalized.

Keywords Open-pit mining · Engineering geological model · Periclinal closure · Bedding orientation · Slope design · Phosphate deposit

1 Introduction

Tunisia ranks among the world's leading producers of phosphate rock, with the Gafsa–Metlaoui basin in the country's southwestern interior forming the geological and economic heart of this industry. The basin hosts some of the richest known accumulations of Paleocene–Eocene phosphorites in the Tethyan province, and its exploitation by the Compagnie des Phosphates de Gafsa (CPG) has sustained national production for over a century (Sassi 1974; Garnit et al. 2012). Within this productive belt, the Oum El Khecheb deposit stands out for both its geological complexity and its continuing strategic importance to national phosphate output.

Open-pit mining of stratiform phosphate deposits such as Oum El Khecheb required a thorough, site-specific understanding of the geological, lithological, and morpho-structural conditions that control ore-body geometry and the mechanical behavior of the surrounding rock mass. These two aspects are closely interrelated: the geometry of phosphate horizons determines the dimensions and economics of the mining operation, while the mechanical properties of the surrounding formations control the permissible slope angles, the risk of bench failure, and the long-term stability of the pit walls. Both ore-body geometry and rock-mass behavior are strongly influenced by the tectonic evolution of the area.

The Oum El Khecheb structure is distinguished by a geostructural configuration that has been modified by folding, differential erosion, and regional-scale tectonic deformation associated with the Atlasic compression phases (Zargouni 1986). As a consequence, the phosphate and marl–carbonate sequence exhibits heterogeneous mechanical and geometrical properties that vary substantially from one sector of the deposit to another. This spatial heterogeneity is particularly pronounced in the eastern closure of the pit, the terminal zone where the excavation approaches its structural and operational boundary (Burollet 1956; Sassi 1974; Yaich et al. 2000). Here, the progressive attenuation of the anticlinal fold introduces spatial variability in bedding orientation, the convergence of structural discontinuities creates a complex rock mass (Zargouni 1986; Ahmadi 2006), and variable lithological contacts combined with perched groundwater conditions generate additional challenges for safe and efficient mining operations.

Despite the strategic importance of the eastern closure as a mining front, this sector has received relatively limited systematic geological documentation in the published literature. Most previous investigations of the Oum El Khecheb deposit have focused on broader stratigraphic and geochemical aspects at the basin scale, leaving a gap in the detailed, integrated characterization required for mine planning and operation (Sassi 1974; Yaich et al. 2000; Galfati et al. 2010; Garnit et al. 2012). The present study was specifically designed to address this gap.

The objectives of this study are to: (i) establish the lithostratigraphic framework of the Oum El Khecheb eastern closure; (ii) characterize the structural features that affect phosphate continuity and govern rock mass geometry; (iii) perform statistical and spatial analysis of the key geological parameters with particular emphasis on the case-study zone rather than focusing solely on dip measurements (iv) integrate these elements into a coherent three-dimensional geological model that can serve as a foundation for resource estimation, mine planning, and slope stability analysis.

2 Geological and Structural Setting

2.1 Location and Access

The Oum El Khecheb phosphate deposit is situated in the Gafsa–Metlaoui basin of southwestern Tunisia (Fig. 1), approximately 25 km west of the city of Gafsa and contiguous with the Metlaoui administrative area, from which the deposit extends eastward for approximately 11 km.

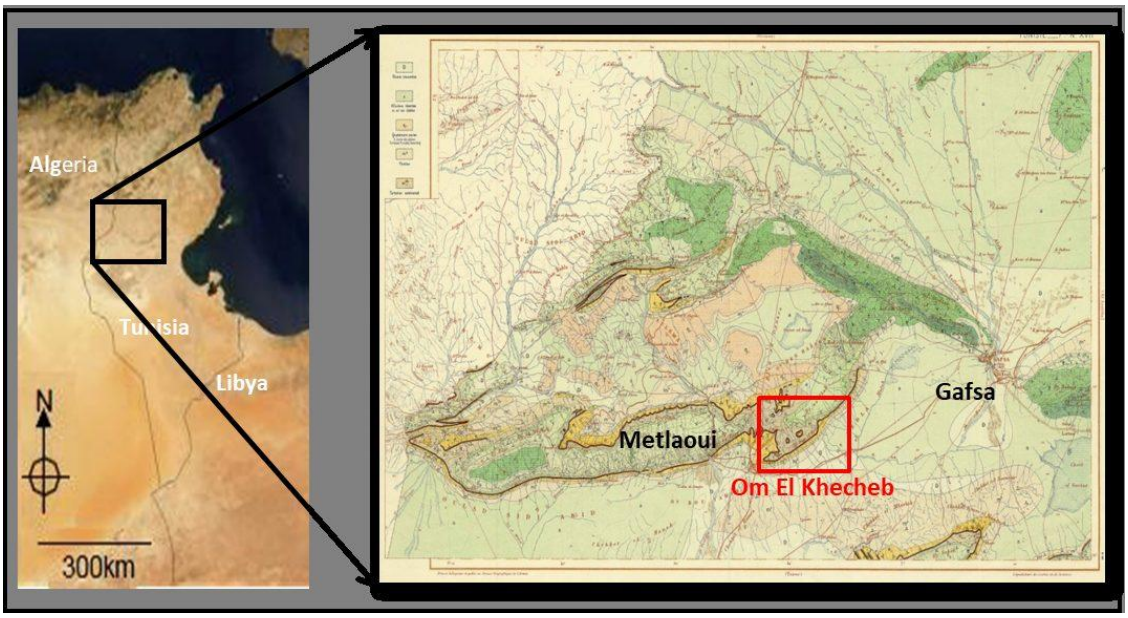


Fig. 1 Geographical location of the Oum El Khecheb phosphate deposit within the Gafsa–Metlaoui basin, south-western Tunisia. The inset shows the regional position within North Africa

The main access route follows the Gafsa–Metlaoui highway, which runs along the southern margin of the deposit, while several secondary tracks provide access to individual mining areas. The most historically significant of these tracks was originally constructed to transport phosphate from the Oum El Khecheb extraction zones to the M'Dhilla processing plant during the early 1980s, and it remains an important logistical artery for current operations (Fig. 2).

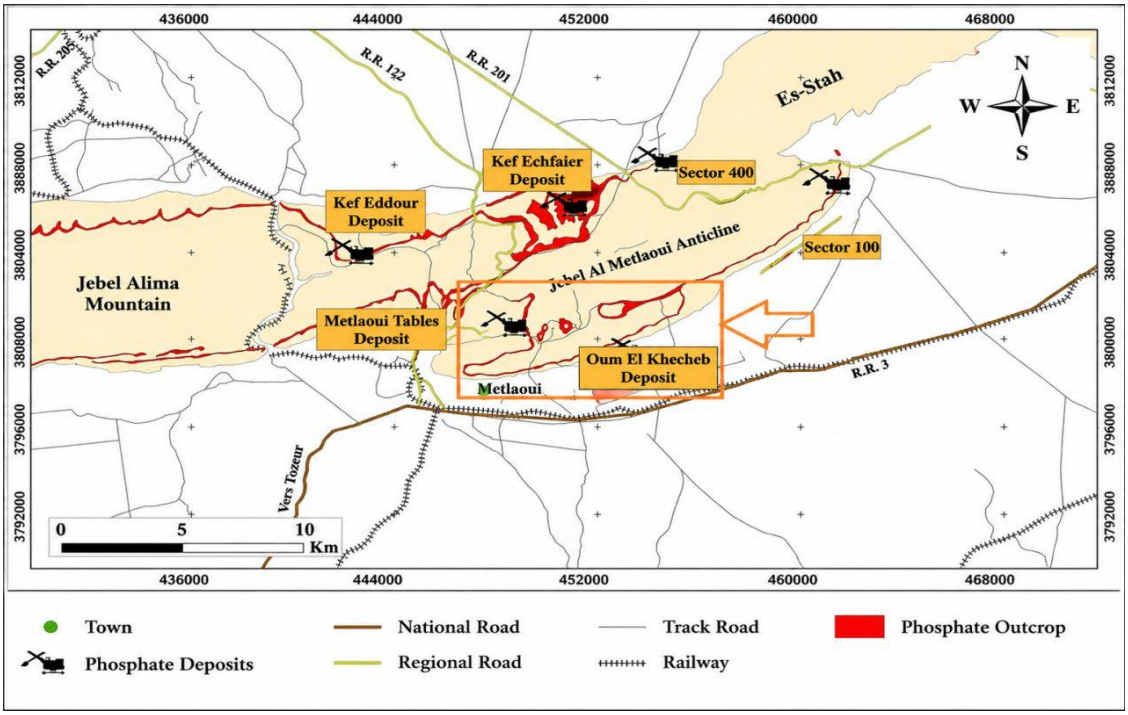
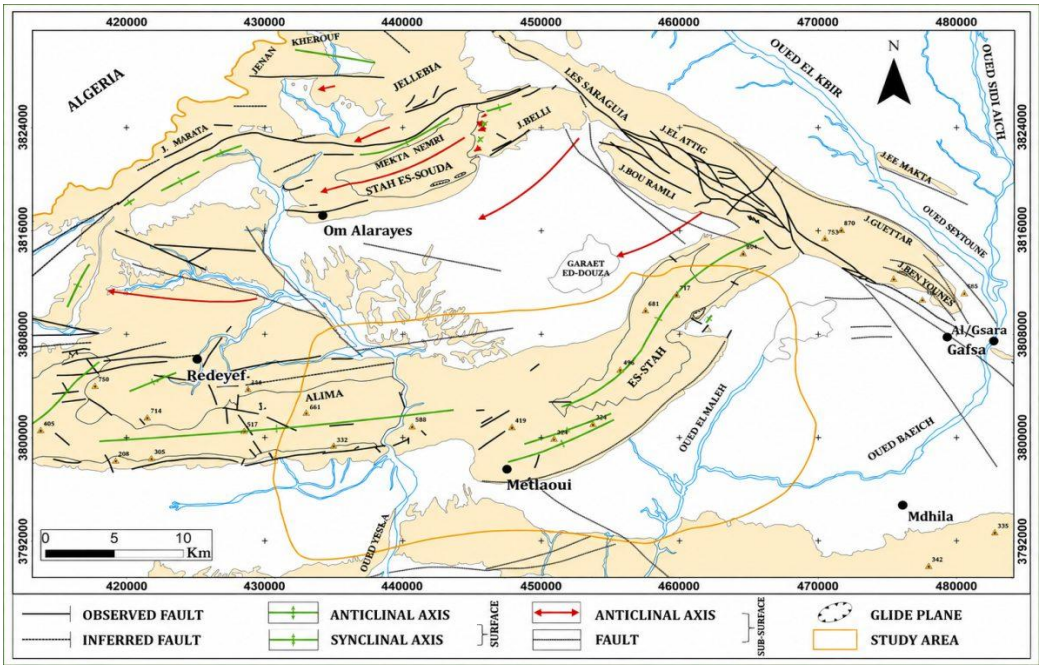


Fig. 2 Access routes to the Oum El Khecheb deposit, showing the main Gafsa–Metlaoui highway and the secondary mining tracks, including the historical phosphate transport track to the M'Dhilla processing plant

2.2 Regional Structural Framework

Geomorphology examines the interactions between geological factors including lithological and tectonic setting, and surface erosion phenomena. Accordingly, geomorphological features record the interplay among sedimentation, tectonic deformation, and erosion (Legier 1977; Deffontaines et al. 2008). The structural evolution of the Gafsa–Metlaoui basin has been characterized by numerous authors as a product of multi-phase Atlasic tectonics operating within a broader geodynamic framework of Africa–Eurasia convergence (Zargouni 1986; Zouari 1995). The Gafsa basin lies at the southern margin of the Atlasic fold-and-thrust belt, which follows the east–west trace of the South Atlas Fault a major structural discontinuity extending from Agadir in Morocco to Gabes in Tunisia along a general N120° trend. Within this tectonic corridor, the basin has been affected by successive phases of compression and extension that produced a characteristic pattern of en-échelon anticlines, perched synclines, and transpressional faults (Zargouni 1986; Zouari 1995).

The Oum El Khecheb area forms part of a regional folded chain extending from Kef EchChougga, northwest of Sidi Ahmed Zarroug, to Foum El Khanga, south of Tameghza (Fig. 3a). This chain encompasses the Jebel Stah, Zerf, Alima, and Belligui ranges a series of en-échelon anticlinal ridges with E–W to SW–NE axes (N80°–N90°), locally deflected by N60° transtensional faults that separate the ridges from enclosed intermontane plains. The anticlines are bounded to the north by the Moularès Syncline and to the south by the Metlaoui–Gafsa Syncline, with the anticlinal flanks typically showing steeper dips on the southern side and more gentle, knee-shaped dip patterns on the northern side a geometric asymmetry consistent with NW-directed Atlasic compression (Zargouni 1986; Zouari 1995).



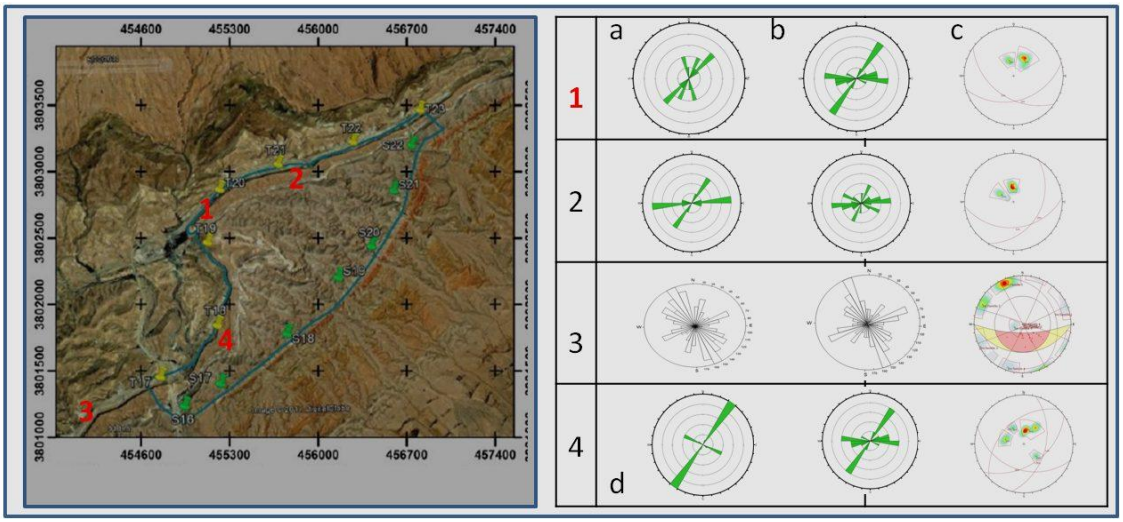


Fig. 3 Regional and local structural data. a Structural map of the Gafsa–Metlaoui basin showing the main anticlinal and synclinal structures, the fault systems and the position of the Oum El Khecheb anticline (Zargouni 1986; Boukadi et al. 1991). b Multi-station structural analysis of the eastern closure: rose diagrams of discontinuity strikes in the upper limestone of the Kef Eddour Formation (b1) and in the lower limestone of the same formation (b2), and stereographic projection of poles to discontinuity planes (b3). Equal-area projection, lower hemisphere

At the deposit scale, the present study shows that the Oum El Khecheb structure corresponds to an anticline whose axis is oriented ENE–WSW. Its morpho-structural expression has been significantly modified by differential erosion, which has dismantled the anticlinal hinge in its eastern part. As a result, the eastern pericline termination displays a zone of gentle bedding dip, typically between 10° and 25°, overlain by a resistant lower limestone slab that caps the eroded fold core. In contrast, the western part of the deposit, in the direction of the Mouileh area, is characterized by a progressive eastward increase in dip reaching 30° to 35° at surface outcrops, a structural gradient that has direct implications for pit slope design and ore recovery (Zargouni 1986) (Fig. 3b).

2.3 Lithostratigraphy

The Gafsa–Metlaoui basin forms part of the southern Atlas domain and contains a sedimentary succession ranging from the Upper Cretaceous to the Middle Eocene (Burollet 1956; Sassi 1974; Yaich et al. 2000)). This succession records the evolution of a shallow-marine carbonate–phosphatic platform along the southern margin of the Tethys, periodically interrupted by regressive episodes that introduced terrestrial and lagoonal facies.

The lithostratigraphic units exposed in the study area (Figs. 4 and 5) have been documented by several authors (Burollet 1956; Sassi 1974; Yaich et al. 2000; Galfati et al. 2010) and can be summarized, from base to top, as follows. The Upper Cretaceous Abiod Formation comprises compact, white to cream-colored limestones and chalks that form the structural basement of the phosphate-bearing sequence in most of the basin. Overlying this unit, the Paleocene El Haria Formation consists of gray-green calcareous marls with abundant planktonic foraminifera, representing the transgressive base of the Paleocene cycle. Above it and in the same age formed the alternating evaporite and marls of the Thelja Formation. The economically critical Chouabine Formation (Lower Eocene, Ypresian) contains the phosphate-rich horizons peloidal and bioclastic phosphorites interbedded with calcareous marls that constitute the principal ore zone at Oum El Khecheb. The overlying Metlaoui Formation (Lower to Middle Eocene) is dominated by thick nummulitic limestones that form a mechanically competent cap rock above the phosphatic sequence. The succession is locally capped by the Kef Eddour Member and the Jebs Formation, comprising gypsiferous marls and evaporites, and by a discontinuous veneer of Neogene to Quaternary continental deposits (Hlaiem 1999).

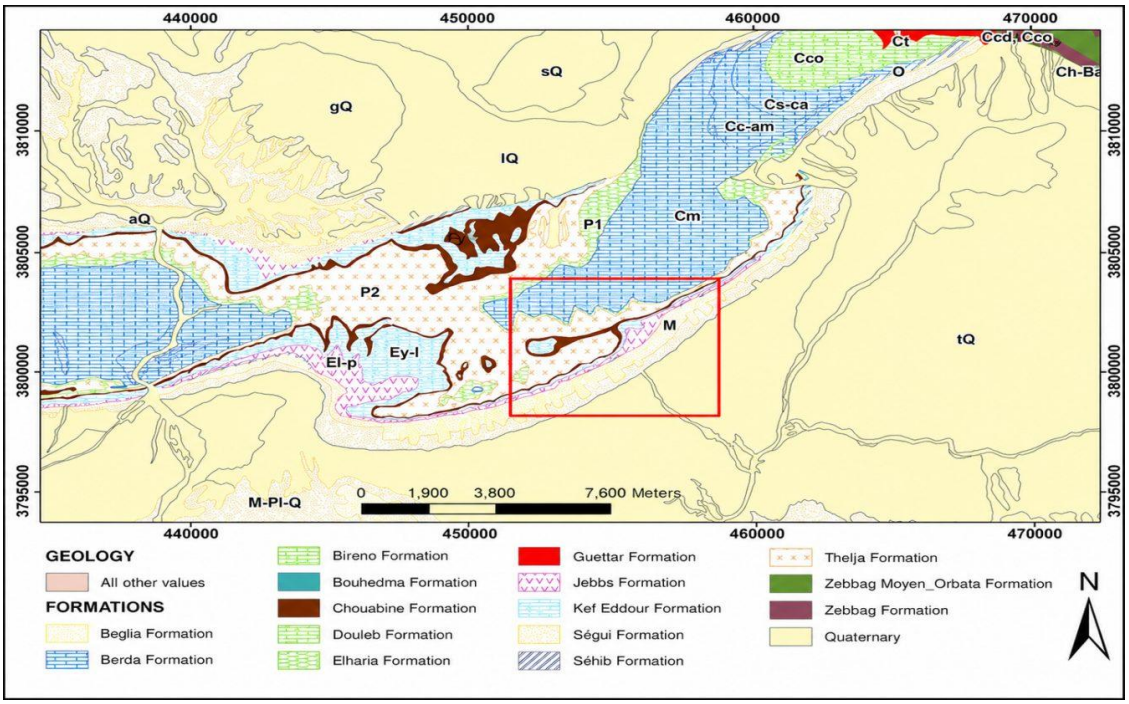


Fig. 4 Geological map of the Gafsa–Metlaoui basin showing the lithostratigraphic distribution of the principal formations

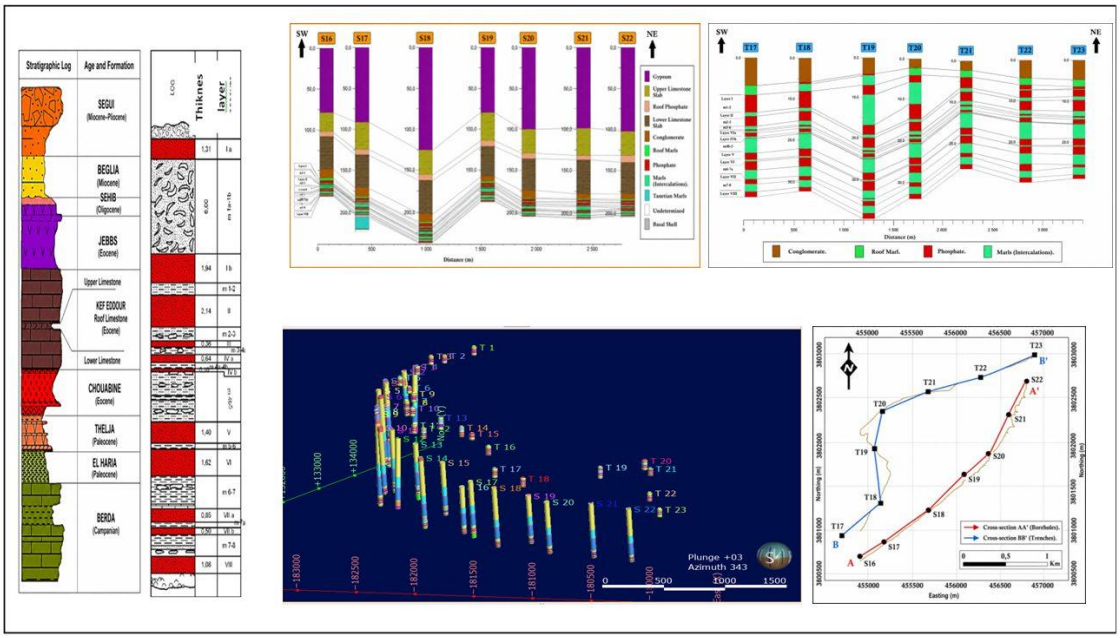


Fig. 5 Lithostratigraphic log correlation across the eastern closure of Oum El Khecheb

This lithostratigraphic succession records a Paleocene–Eocene depositional history controlled by eustatic sea-level fluctuations and nutrient-rich upwelling currents along the North African continental margin (Föllmi 1996; Galfati et al. 2010; Garnit et al. 2012). The phosphate accumulation is interpreted within the framework of a condensed marine carbonate–phosphorite system in which episodic reworking, winnowing, and diagenetic transformation of biogenic precursors generated the high-grade peloid-dominated phosphorites now exploited at Oum El Khecheb (Hlaiem 1999).

3 Materials and Methods

The geological characterization presented in this study draws on a multi-source database assembled specifically for the eastern closure sector of the Oum El Khecheb pit. Five principal data types were integrated.

Exploration drillholes provide the primary subsurface control on lithological succession and ore-zone geometry. Core logs descriptions document the nature and thickness of each lithological unit, including precise recording of the positions of phosphate horizons, intercalated marly interbeds, and contact depths with the Metlaoui limestone cap rock and the Thelja substrate.

Geological field mapping was conducted to confirm the existing maps and to update them and generate the needed ones across the accessible pit benches and surrounding outcrops, focusing on the accurate delineation of lithological contacts, fault traces, and bedding orientation measurements. Structural data including strike, dip direction, dip magnitude, and the nature of discontinuity planes were recorded systematically and processed using stereographic projection techniques.

Bench face observations provided real-time geological control during active mining operations. Sequential logging of exposed bench faces allowed the correlation of lithological contacts between drillhole intercepts and the construction of reliable longitudinal and transverse cross-sections through the eastern closure.

Topographic surveys, including digital terrain model (DTM) generation and slope analysis, were used to characterize the morphological expression of the geological structure and to support the construction of the three-dimensional geological model. Slope maps generated from the DTM identify zones of differential erosion and structural control on the present-day topography.

Production records, comprising new recent mining data on ore tonnage, bench positions, and face configurations, were used to reconstruct the progressive geometry of the excavation and to verify the consistency of the geological model with actual operational experience. Fig. 6 shows the geological map of the Oum El Khecheb deposit derived from the integration of these data sources.

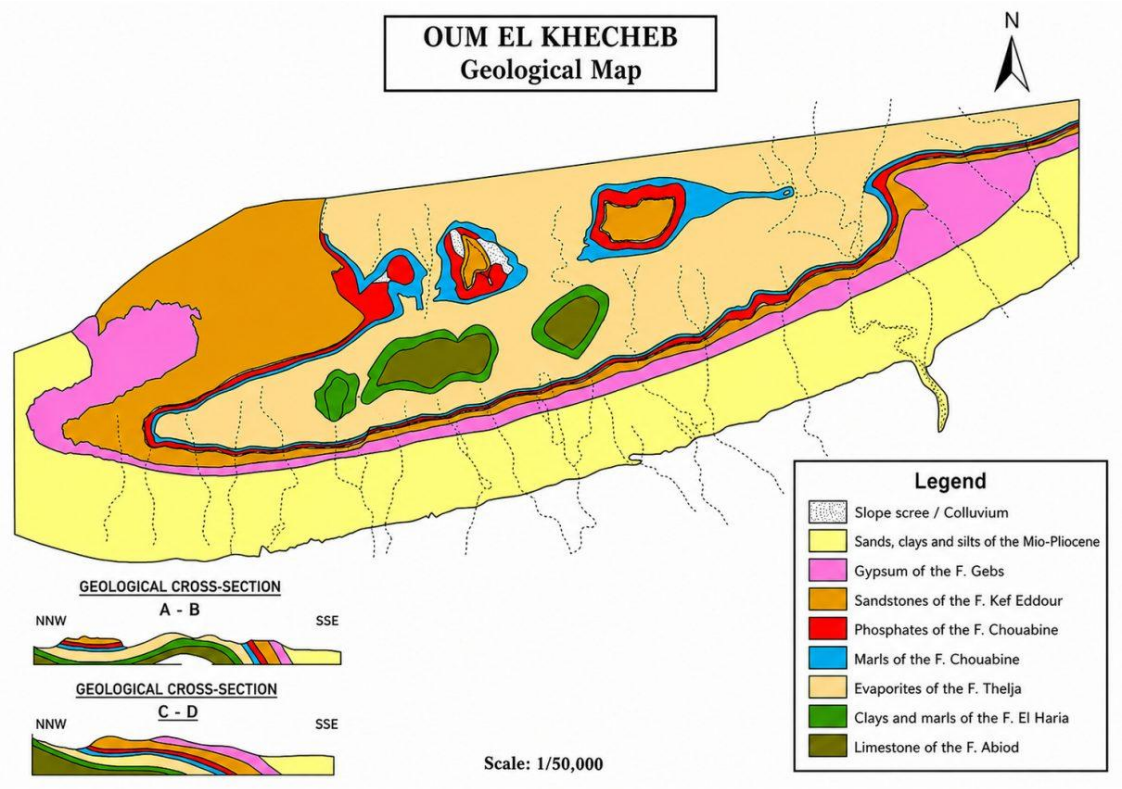


Fig. 6 Geological map of the Oum El Khecheb deposit derived from the integration of drillhole data, field mapping and bench-face observations

4 Results

4.1 Geological Configuration of the Eastern Closure

A thorough understanding of the geological controls governing grade distribution and lithological continuity within a phosphate deposit is a prerequisite for robust resource estimation and mine planning. In modern practice, three-dimensional geological modeling has become an indispensable tool for translating field and subsurface observations into a spatially explicit representation of the ore body and its enclosing rock mass (Fig. 7a). At Oum El Khecheb, the eastern closure exhibits a geological configuration that departs markedly from the more extensively documented central part of the deposit, and which merits specific characterization (Fig. 7b).

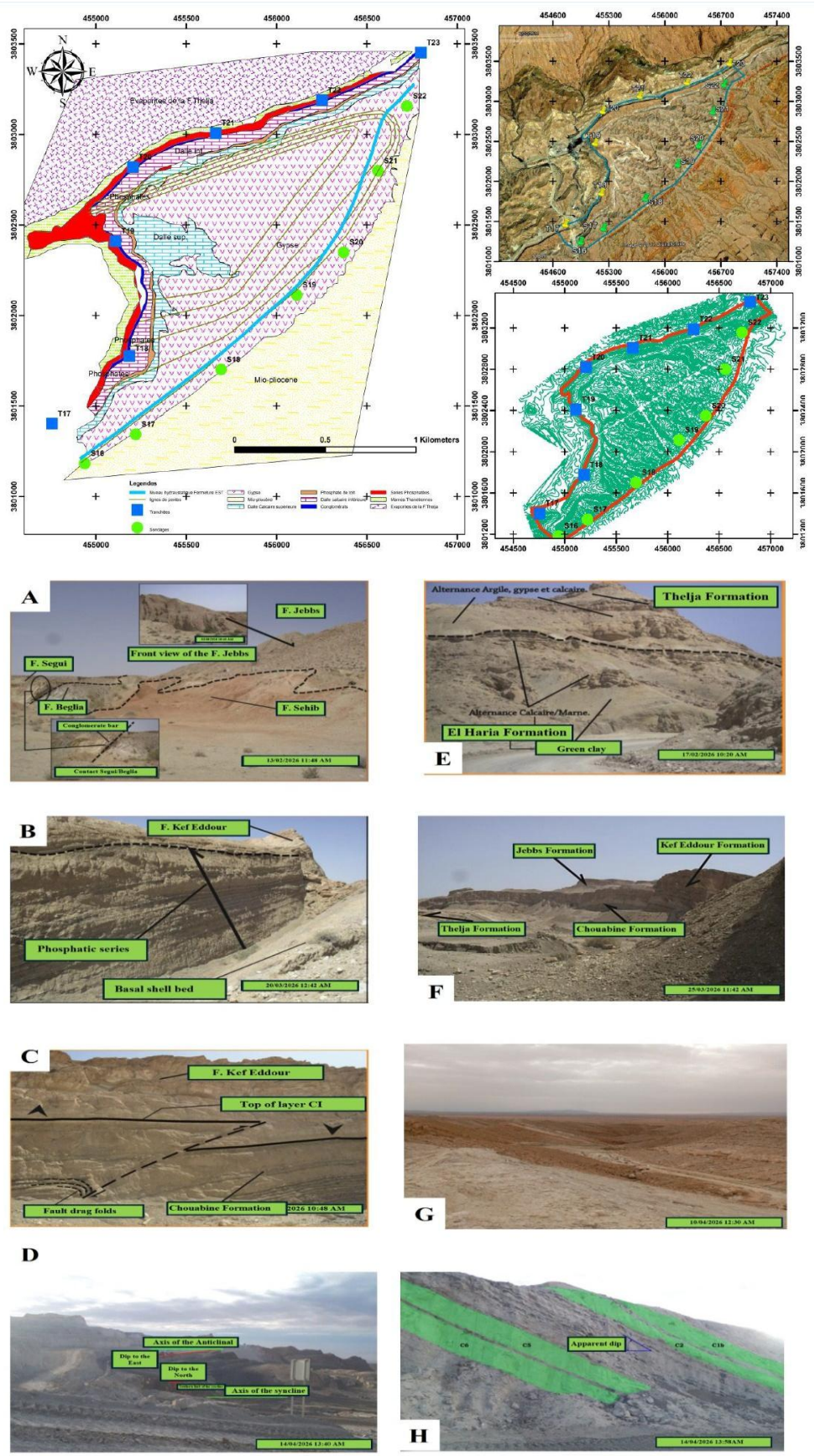


Fig. 7 Geological configuration of the eastern closure. a Geological description panel showing the distribution of lithological units and the principal structural features. b Geological delineation of the eastern closure and the Gafsa Fault in the Metlaoui plateau

The present study shows that eastern closure sector is characterized by the progressive structural and topographic simplification of the Oum El Khecheb anticline as it plunges eastward. In contrast to the well-defined, steeply dipping flanks observed in the central pit, the eastern closure exposes gently dipping beds whose orientation changes gradually over short horizontal distances. Structural analysis documents the progressive eastward attenuation of the Oum El Khecheb anticline, with bedding dip decreasing from approximately 30°–45° in the western sector to 10°–25° toward the eastern pericline. This geometric complexity is captured in the topographic numerical model (Fig. 8), and reveals a dissected periclinal morphology that reflects the underlying structural configuration. The eastern sector is characterized by an asymmetric synclinal geometry, with the northern flank occurring at a higher structural level than the southern flank. This asymmetry marks the transition toward the eastern closure of the anticline, where recent measurement of the bedding dips progressively decrease downstream and the entire structure plunges toward the east.

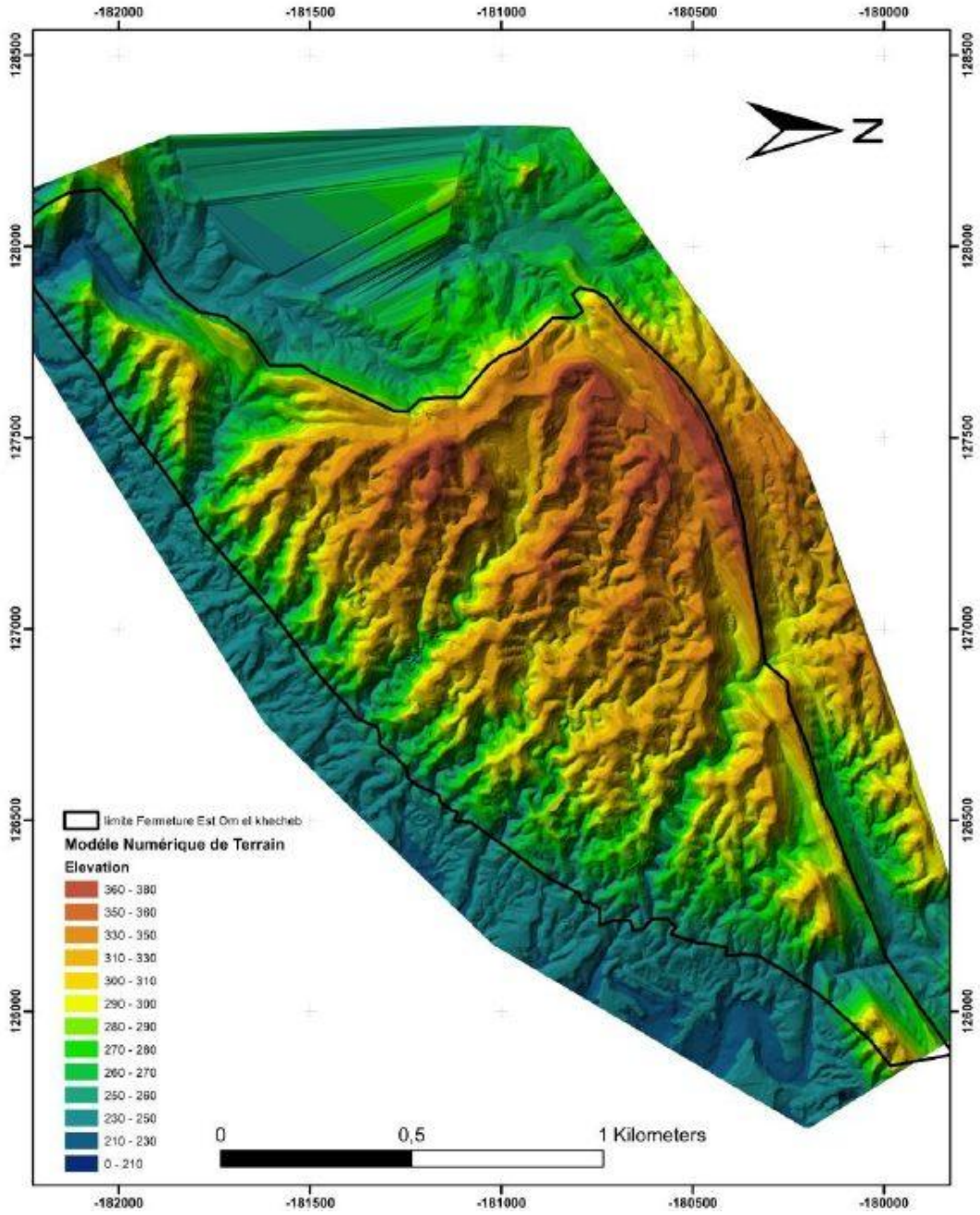


Fig. 8 Digital terrain model of the eastern closure of the Oum El Khecheb pit, derived from photogrammetric survey. Contour interval 5 m

Phosphate horizon thickness and the proportion of intercalated marly material both vary across the eastern closure (Fig. 9). The phosphate layers thin progressively toward the pericline nose, reflecting the attenuation of accommodation space during deposition and the effects of post-depositional erosion at the anticlinal crest. Conversely, the intercalated marls which represent mechanically weak interbeds within the phosphate sequence maintain a more consistent thickness, meaning that the net-to-gross phosphate ratio decreases toward the eastern extremity of the deposit. This relationship and after combining the recent done mining data shows a direct implications for ore grade modeling and for the selection of selective mining techniques in this sector.

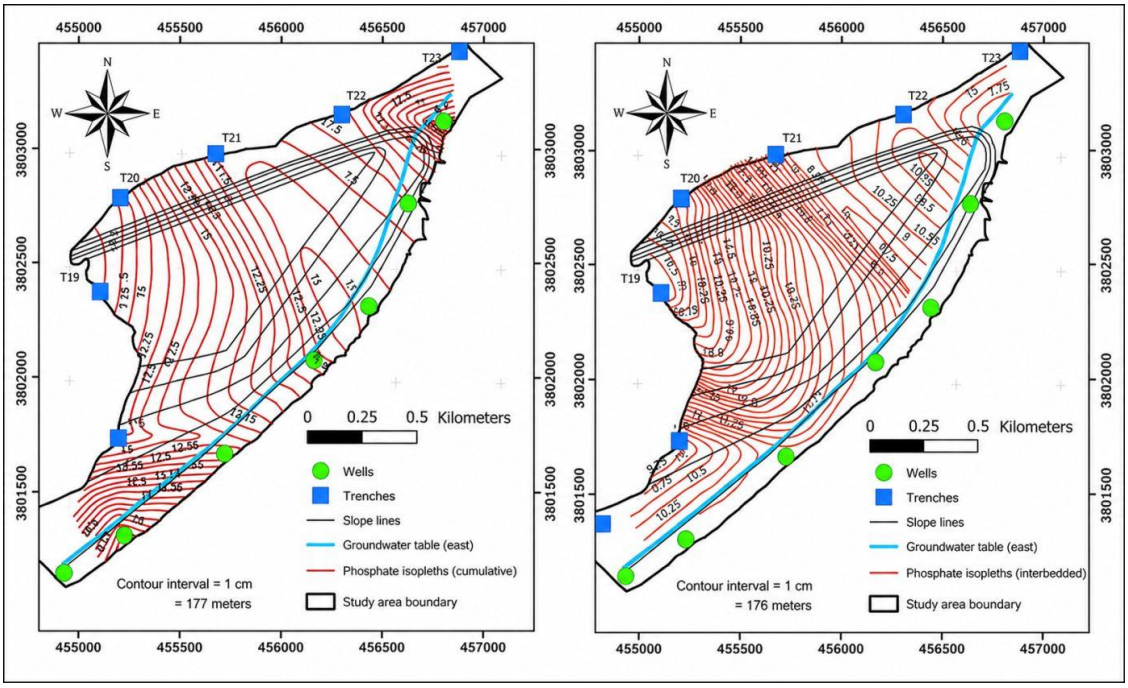


Fig. 9 Spatial distribution of phosphate horizon thickness and of intercalated marl thickness across the eastern closure of the Oum El Khecheb deposit

The overburden thickness map (Fig. 10) confirms that the depth to the top of the phosphate horizon increases toward the east as the overlying Metlaoui limestone cap rotates into a sub-horizontal position above the periclinal nose (Galfati et al. 2010; Galai and Sliman 2019). This geometry requires careful management of the stripping ratio in advance of phosphate extraction, particularly where the limestone cap attains its maximum preserved thickness and dip (Fig. 11b).

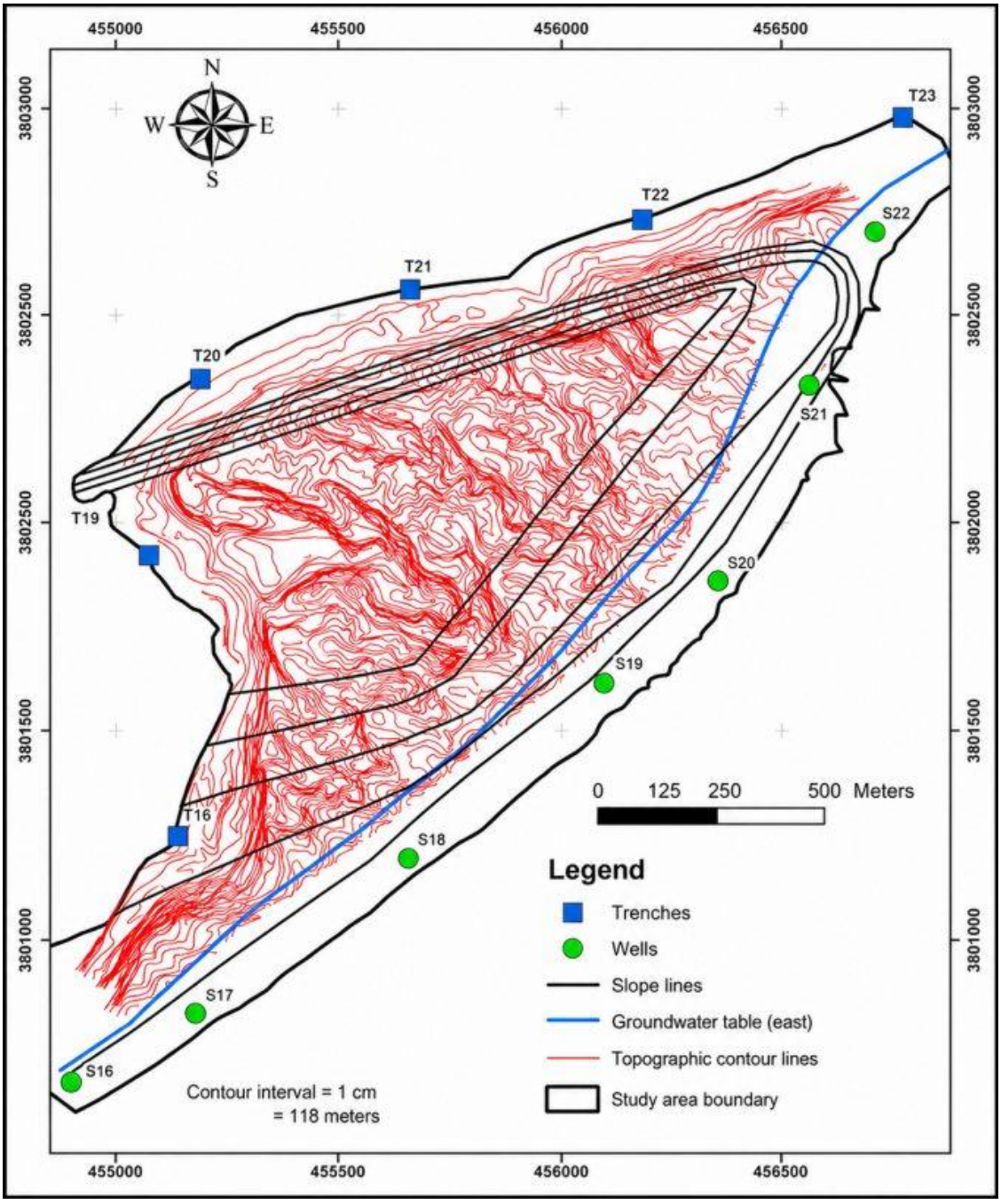


Fig. 10 Overburden thickness map of the eastern closure of the Oum El Khecheb deposit

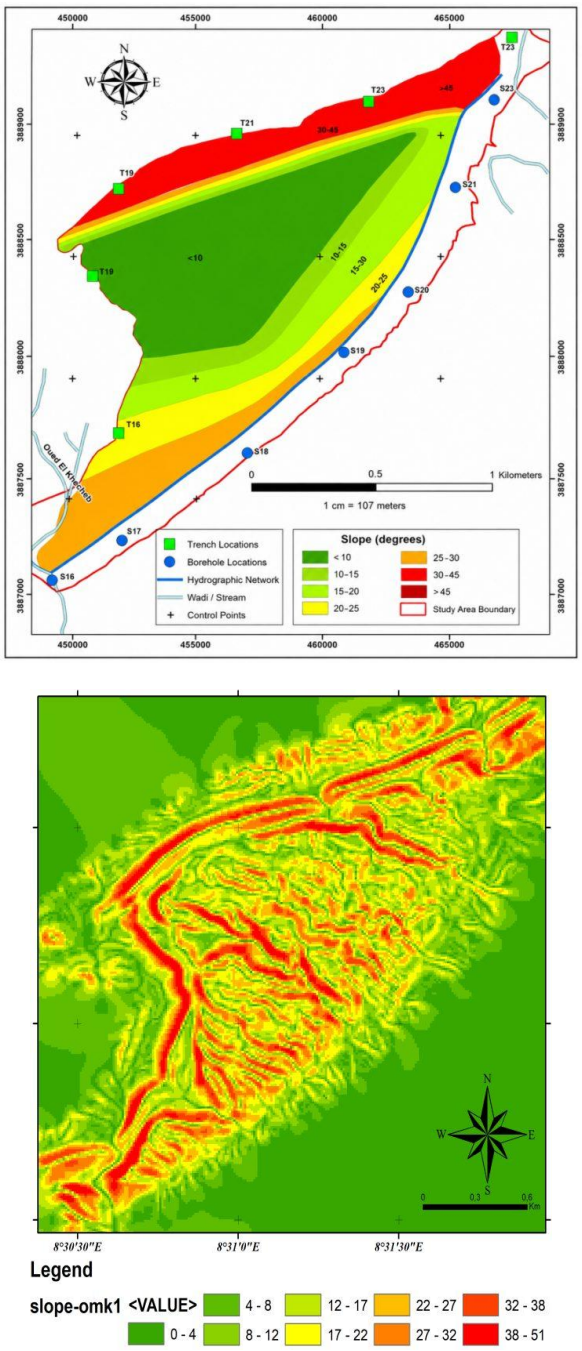


Fig. 11 Slope angle distribution maps of the eastern closure derived from the digital terrain model. a Slope of the phosphate layers. b Slope of the overburden

4.2 Statistical Analysis of Phosphate Horizon Thickness

The dataset combines two types of observation: trenches (T17–T23) on the northern flank and in the central part of the structure, and boreholes (S17–S22) on the southern flank, where the phosphate series lies at 188–240 m depth. Data type therefore coincides with structural position, and the two effects cannot be separated with the present dataset. This matters because the two methods can record thickness differently. Trench faces expose the phosphate contacts directly. Borehole thicknesses may be underestimated where core recovery is poor in friable phosphate intervals, or overestimated if apparent thicknesses in vertical holes are not corrected for bedding dip. The lower mean thickness of the southern flank (10.85 m, compared with 12.34 m on the

northern flank and 14.28 m on the crest) is therefore interpreted with caution: it may reflect genuine structural or depositional thinning, a methodological bias, or both. Paired trench–borehole observations at the same locations, or core-recovery records for the S-series boreholes, would allow this effect to be quantified.

Statistical analysis of phosphate horizon thickness across the 13 investigated cross-sections (S17–S22, T17–T19 and T20–T23) provides the quantitative basis of the three-dimensional geological model of the eastern closure. The phosphate body has an overall mean thickness of 12.10 m (Table 1), with individual section values ranging from 8.60 to 14.82 m. The sample standard deviation is 1.91 m, which gives a coefficient of variation of 15.8%. The phosphate horizon is present and correlatable in all 13 sections, and its thickness variability is moderate and spatially organized rather than random, as shown below.

Table 1 Quantitative parameters of the phosphate horizon across the eastern closure of Oum El Khecheb

Parameter	Northernflank	Central structure	Southernflank	EntireDeposit
Number of exploration boreholes/trenches	4	3	6	13
Borehole/trenchesnames	T23-22-21-20	T19-18-17	S17-18-19-20-21-22	
Boreholespacing (m)	400–500	400–500	400–500	
Borehole/trenches depth range (m)	26–33	32–40	188–240	
Total drilledlength (m)	118.43	104.78	1270.42	1493.63
Phosphate thickness – Minimum (m)	11.31	13.74	8.60	8.60
Phosphate thickness – Maximum (m)	14.54	14.82	12.96	14.82
Mean phosphate thickness (m)	12.34	14.28	10.85	12.10
Standard deviation	1.49	0.54	1.60	1.91
Coefficient of variation (%)	12.07	3.78	14.75	15.81

σ is the sample standard deviation (n − 1) and CV = σ/mean. Trenches (T17–T23) were logged on the northern flank and above the structural crest; boreholes (S17–S22) were drilled on the southern flank, where the phosphate series lies at 188–240 m depth

Spatial analysis of the section data reveals a systematic thickness variation across the structure. Sections T17–T19, in the central part of the closure above the structural crest, record the highest sub-group mean of 14.28 m over a narrow range of 13.74–14.82 m (σ = 0.54 m; CV = 3.78%) and include the dataset maximum. Sections T20–T23, on the northern flank, give an intermediate mean of 12.34 m (range 11.31–14.54 m; σ = 1.49 m; CV = 12.07%). Sections S17–S22, on the southern flank, record the lowest mean of 10.85 m (range 8.60–12.96 m; σ = 1.60 m; CV = 14.75%) and include the dataset minimum of 8.60 m. The phosphate horizon is therefore thickest and most regular above the structural crest and thinner on both flanks, the southern flank being both the thinnest and the most variable. Because fold geometry alone does not modify the true thickness of a bed, this pattern is attributed either to syn-depositional thickness variation related to the growing structure, or to thinning of the more steeply dipping limb during folding; discriminating between these requires thickness to be plotted against bedding dip for each section.

For the dataset as a whole, thickness variability is moderate (mean 12.10 m; σ = 1.91 m; CV = 15.8%) and follows a coherent spatial pattern rather than random scatter, which is favourable for resource estimation. A denser dataset, including paired trench and borehole observations, would be required to model thickness continuity by variography and to support a formal resource classification (Sinclair and Blackwell 2002; Rossi and Deutsch 2014). The minimum recorded thickness of 8.60 m constrains the local ore geometry, whereas the

economic limit of extraction in this sector depends on cut-off criteria (minimum mining thickness, stripping ratio and P2O5 grade) that lie outside the scope of this study.

4.3 Structural Segmentation of the Deposit

Detailed structural analysis of the Oum El Khecheb deposit reveals significant and spatially organized variations in both the magnitude and direction of bedding dip throughout the mineralized body. These variations are a direct expression of the complex tectonic history of the area, which records successive phases of folding, faulting, and differential deformation associated with the Atlasic compressional phases and their subsequent partial relaxation during Neogene extension (Zargouni 1986; Zouari 1995). As a consequence, the phosphate layers do not behave as a single, geometrically homogeneous unit; rather, they exhibit a systematic progression of attitudinal change from the more steeply dipping western sectors toward the gently dipping eastern pericline.

To account for this structural heterogeneity within a framework suitable for reserve estimation and mine planning, the deposit was subdivided into a series of structurally coherent intervals based on the progressive attenuation of the fold amplitude along the longitudinal axis of the anticline (Fig. 11a). Each interval represents a domain within which bedding orientation, layer continuity, and geometric configuration are sufficiently uniform to be treated homogeneously in the geological model. The boundaries between intervals correspond to zones of measurable inflection in dip magnitude or direction, identified from the integration of borehole data, surface mapping, and bench face observations.

The structural segmentation serves several functions in mine design. At the most fundamental level, the geometry of the phosphate layers directly determines the calculation of ore volumes, stripping ratios, and recoverable reserves; an assumption of uniform dip across the entire deposit would introduce systematic bias and could lead to significant over- or under-estimation of available resources. By incorporating local structural variations into the reserve model, the geological representation more faithfully reproduces the actual configuration of the phosphate body, thereby enhancing the reliability of resource and reserve declarations.

The structural segmentation also provides essential input for mine planning and exploitation design. Variations in dip angle influence the optimal orientation of mining benches, the configuration of inter-ramp slopes, the efficiency of stripping operations, and the layout of haul roads. Sectors with steeper dip require more conservative slope angles and may necessitate specific excavation procedures and enhanced slope monitoring, whereas gently dipping sectors are better suited to conventional open-pit extraction with wider, lower-risk bench configurations. The structural intervals established from the attenuation pattern of the Oum El Khecheb fold therefore serve both as geological modeling units and as mine design domains, ensuring that the geological complexity of the deposit is systematically propagated into operational planning decisions.

4.4 Geological Mapping and Three-Dimensional Model

The eastern closure of the Oum El Khecheb structure exhibits a distinctly more complex topographic and geological profile than the central portion of the anticline, reflecting the progressive decrease in fold amplitude and the differential erosional response of the contrasting lithological units. The relationship between the geological structure and the present-day topography is particularly clear in the eastern sector: resistant limestone beds of the Metlaoui Formation form prominent ridges and benches, while the less competent marly and

evaporite intervals of El Thelja and Chouabine Formations occupy recessive topographic positions. This structural control on landscape form confirms that differential erosion, acting on the folded sedimentary sequence, has largely governed the evolution of the present-day terrain and that the geological map provides a reliable framework for extrapolating subsurface conditions between observation points (Fig. 12).

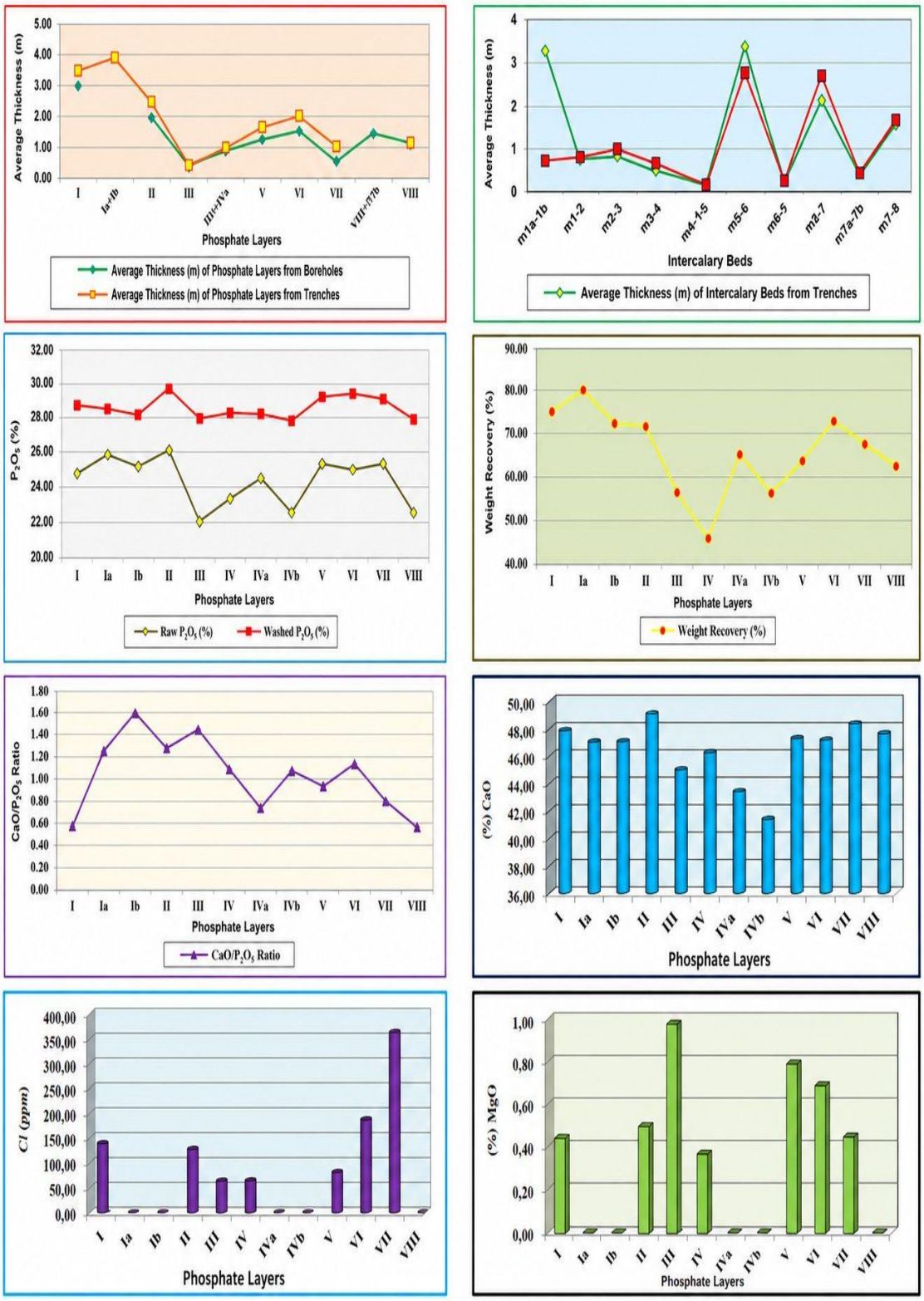


Fig. 12 Statistical analysis of the geological parameters of the eastern closure of Oum El Khecheb

The geological map of the eastern closure (Fig. 13) reveals a clear and coherent succession of Upper Cretaceous to Paleogene formations, with phosphatic horizons interbedded within marl-dominated sequences consistent with the regional stratigraphy of the Gafsa–Metlaoui basin. These lithological relationships confirm that the phosphate deposits are genetically associated with shallow marine sedimentary environments that experienced repeated transgressive–regressive cycles during the Paleocene–Eocene interval. The mapped contacts between lithological units are consistent across the bench faces, exploration trenches, and drillhole intercepts, demonstrating the structural coherence of the deposit and the reliability of the geological interpretation.

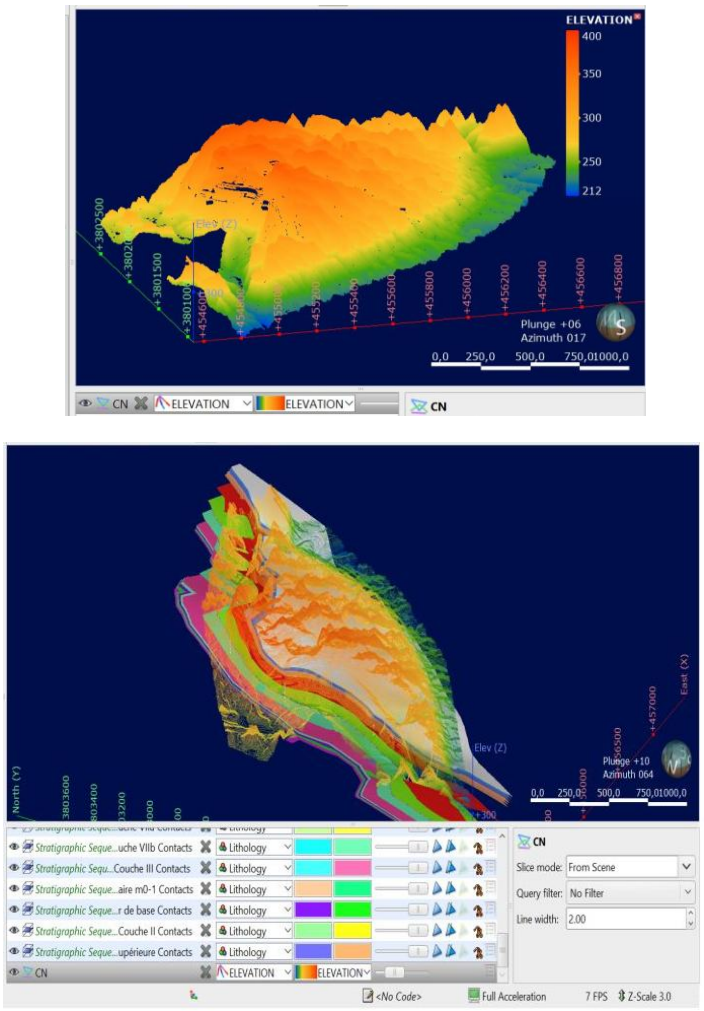


Fig. 13 Topographic and structural profile of the eastern closure, illustrating the relationship between geological structure and landform expression

Field observations, supported by structural cross-sections and orientation measurements, reveal that the deposit is hosted within a well-defined anticlinal structure in the central part of the mine, which transitions northward into a synclinal geometry. The entire structural system plunges toward the east, generating the periclinal closure that defines the eastern limit of the current exploitation area. This geometric configuration controls both the distribution of lithological units at surface and at depth, and the spatial continuity of the phosphate horizons across the mine area (Figs. 12 and 13).

Correlation between adjacent cross-sections also reveals lateral variations in the geometry and thickness of the phosphate layers that reflect both tectonic deformation and primary sedimentary controls. While Atlasic folding has imposed the current inclination and geometry of the strata, local variations in bed thickness observed in cross-section are interpreted as reflecting original depositional conditions within the phosphate basin specifically, the interaction between paleo-bathymetric gradients, current reworking intensity, and the availability of biogenic phosphate precursor material. The combined interpretation of the geological map and structural cross-sections thus distinguishes the effects of post-depositional tectonic modification from primary stratigraphic variability, providing a more nuanced and reliable geological model.

Throughout the mapped area, no major structural discontinuities were found to interrupt the fundamental continuity of the principal phosphate horizons, although minor faults and fracture zones locally offset individual beds and introduce heterogeneity at the bench scale. These minor discontinuities influence the hydraulic connectivity of the rock mass, locally affect ore recovery, and can compromise bench face stability; they must therefore be systematically incorporated into detailed mine planning. The overall three-dimensional geological model (Fig. 14) integrates all of these observations into a spatially coherent representation that constitutes the geological foundation for subsequent resource estimation, slope stability analysis, and long-term mine design. Representative sections extracted from this model illustrate the detailed structural geometry of the closure (Fig. 15) and the N–S geometry of the phosphate horizon and its overburden (Fig. 16).

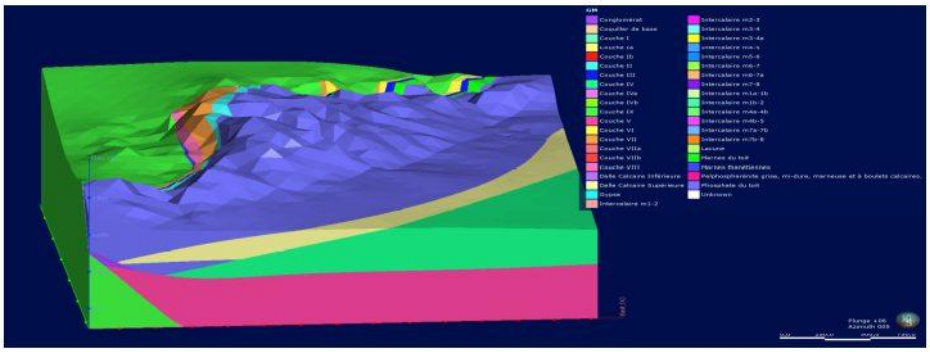


Fig. 14 Three-dimensional geological model of the eastern closure of the Oum El Khecheb deposit, showing the geometry of the principal lithological units and of the phosphate ore horizon

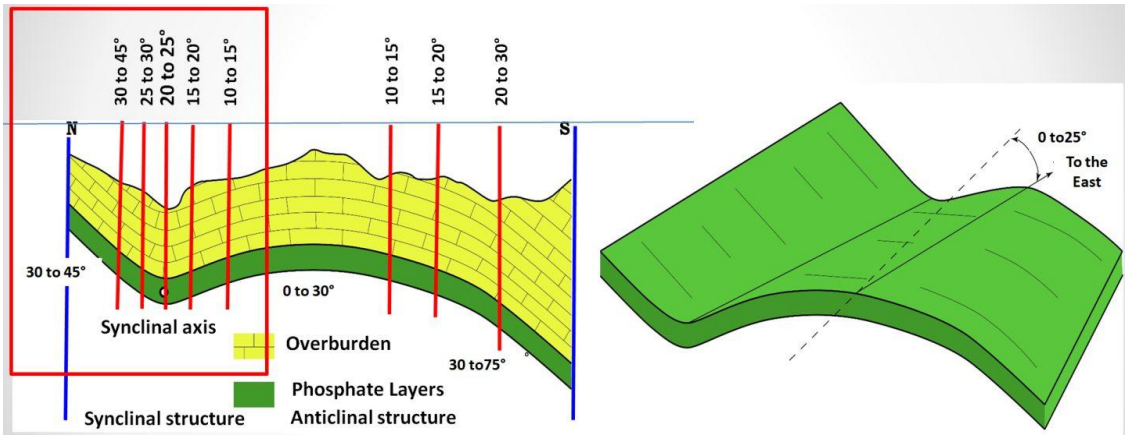


Fig. 15 Detailed structural geometry of the eastern closure, highlighting the slope distribution and the principal lithological contacts

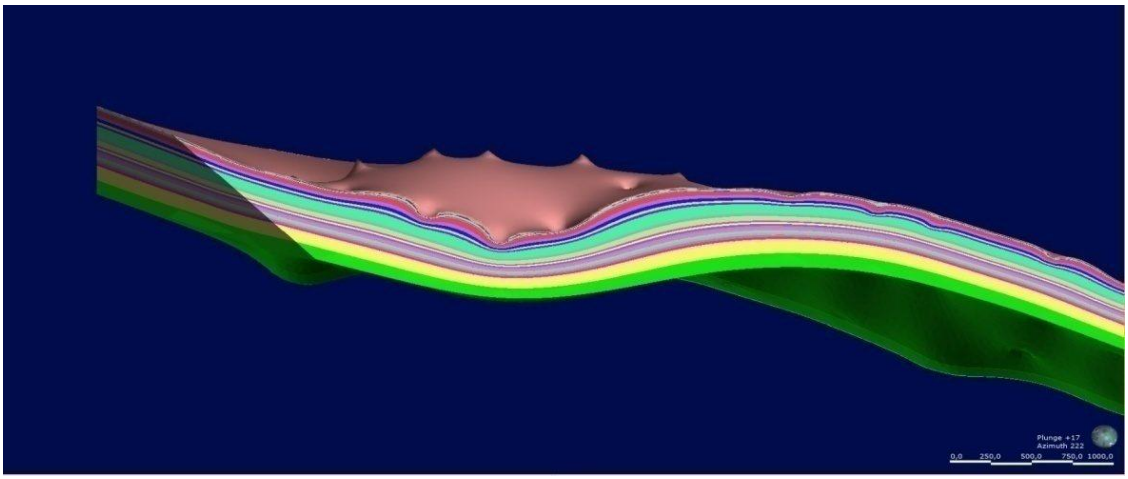


Fig. 16 Representative N–S geological cross-sections through the eastern closure derived from three-dimensional modelling, illustrating the structural geometry and the lithological succession

5 Discussion

5.1 Depositional and Diagenetic Controls on Ore Distribution

The spatial distribution of phosphate grade and horizon thickness observed in the eastern closure of Oum El Khecheb reflects the primary depositional architecture of the Tethyan phosphogenic system as it operated along the North African margin during the Paleocene–Eocene (Föllmi 1996; Galfati et al. 2010; Garnit et al. 2012). Phosphorite accumulation in this setting was fundamentally controlled by upwelling-driven biological productivity, current reworking of skeletal phosphatic material, and the rate of marine sedimentation relative to the rate of phosphate diagenesis. Where upwelling was most intense and sedimentation rates were low, high-grade peloidal phosphorites accumulated; where conditions were more distal or sedimentation rates higher, the ore was diluted by carbonate or marly material, yielding lower-grade intercalated sequences (Galfati et al. 2010; Garnit et al. 2012).

The eastward thinning and grade reduction of the Chouabine phosphate horizons observed in the Oum El Khecheb eastern closure is consistent with a distal-to-proximal facies gradient in which the eastern pericline represents a more marginal depositional setting relative to the main upwelling locus. Comparable lateral grade trends have been documented in other deposits of the Gafsa–Metlaoui basin, including those of Metlaoui,

Mdhilla, and Redeyef (Galfati et al. 2010; Garnit et al. 2012), suggesting that this facies architecture reflects a basin-wide primary control rather than purely local post-depositional modification.

Diagenetic transformation of biogenic precursor phosphate into carbonate-fluorapatite (CFA) the principal mineral phase of the exploitable ore has introduced additional variability at the grain and bed scale. Geochemical data from comparable Tunisian phosphorites indicate that trace element distributions and rare-earth element (REE) patterns in CFA record the redox and diagenetic history of the host sediment (Garnit et al. 2012). The marly interbeds separating the phosphate horizons at Oum El Khecheb are interpreted as representing periods of relatively elevated detrital input and reduced phosphogenic productivity, possibly associated with regressive episodes within the Paleocene–Eocene depositional cycle.

5.2 Tectonic Controls and Structural Inheritance

The structural configuration of the eastern closure results from a polyphase tectonic history, during which the primary depositional geometry of the phosphate series was progressively modified by Atlasic fold-and-thrust deformation. At the regional scale, the southern Tunisian Atlas consists of E–W to ENE–WSW trending folded ranges cut by two major NW–SE fault zones, the Gafsa and the Tozeur–Negrine faults (Zargouni 1986; Deffontaines et al. 2008). The seismicity of the region (Dlala and Hfaiedh 1993) and the Quaternary reactivation of the Gafsa fault (Ben Hassen et al. 2014) show that this compressive regime, with shortening directions ranging from NW–SE to N–S, is still active (Ben Ayed 1986; Bouaziz et al. 2002).

The Oum El Khecheb anticline trends ENE–WSW and plunges eastward at about 25°, forming the periclinal closure examined here. Bedding dip decreases from 30°–45° on the northern flank to 10°–25° near the crest. An ENE–WSW fold axis implies NNW–SSE shortening, which is consistent with the Atlasic compression recorded throughout the southern Tunisian Atlas (Zargouni 1986).

The eastward decrease in structural relief documented in this study reflects the periclinal termination of the fold, where shortening dies out laterally, rather than disruption by a discrete fault.

The absence of major faults disrupting phosphate continuity across the eastern closure, as shown by either bench mapping or drill-hole correlation, has direct economic significance. It implies that ore distribution in this sector is controlled mainly by the primary sedimentary–diagenetic architecture rather than by tectonic offset. This contrasts with other sectors of the Gafsa basin, where NE–SW and NW–SE faults locally offset ore horizons and create hydraulic pathways that complicate dewatering and slope management. The minor discontinuities observed at bench scale are interpreted as brittle reactivation of bedding-parallel anisotropies during late Atlasic and post-Atlasic deformation; their influence on ore continuity is local rather than systematic.

5.3 Implications for Open-Pit Design and Inputs to Slope Stability Analysis

The geological model provides the geometric framework used for ore volume calculation, stripping ratio estimation and bench orientation design; volume and tonnage estimates additionally require grade and density data. The model does not, however, constitute a slope stability assessment. No laboratory or in situ geotechnical testing was carried out in this study: the cohesion, friction angle and shear strength of the phosphate horizon and of the marly interbeds were not determined, and neither kinematic nor limit-equilibrium analyses were performed.

What the dataset does provide are the geometrical inputs on which such analyses depend: the position, thickness and lateral continuity of the marly interbeds; the orientation of bedding around the periclinal closure, where the strike rotates progressively eastward and dip decreases from 30°–45° on the northern flank to 10°–25° near the crest; and the orientation of the bench-scale discontinuities. The marly interbeds are identified as potential weak layers on the basis of their lithology and their persistence across all 13 sections, not on the basis of measured strength. Because the strike of bedding rotates through the periclinal nose, the angle between bedding and the excavated face changes from one bench orientation to the next. Determining which bench orientations are kinematically at risk requires oriented sampling, strength testing and kinematic analysis; the present results indicate where that work should be focused. Figure 17 summarises how each element of the model feeds into open-pit design and into the slope stability analysis that remains to be carried out.

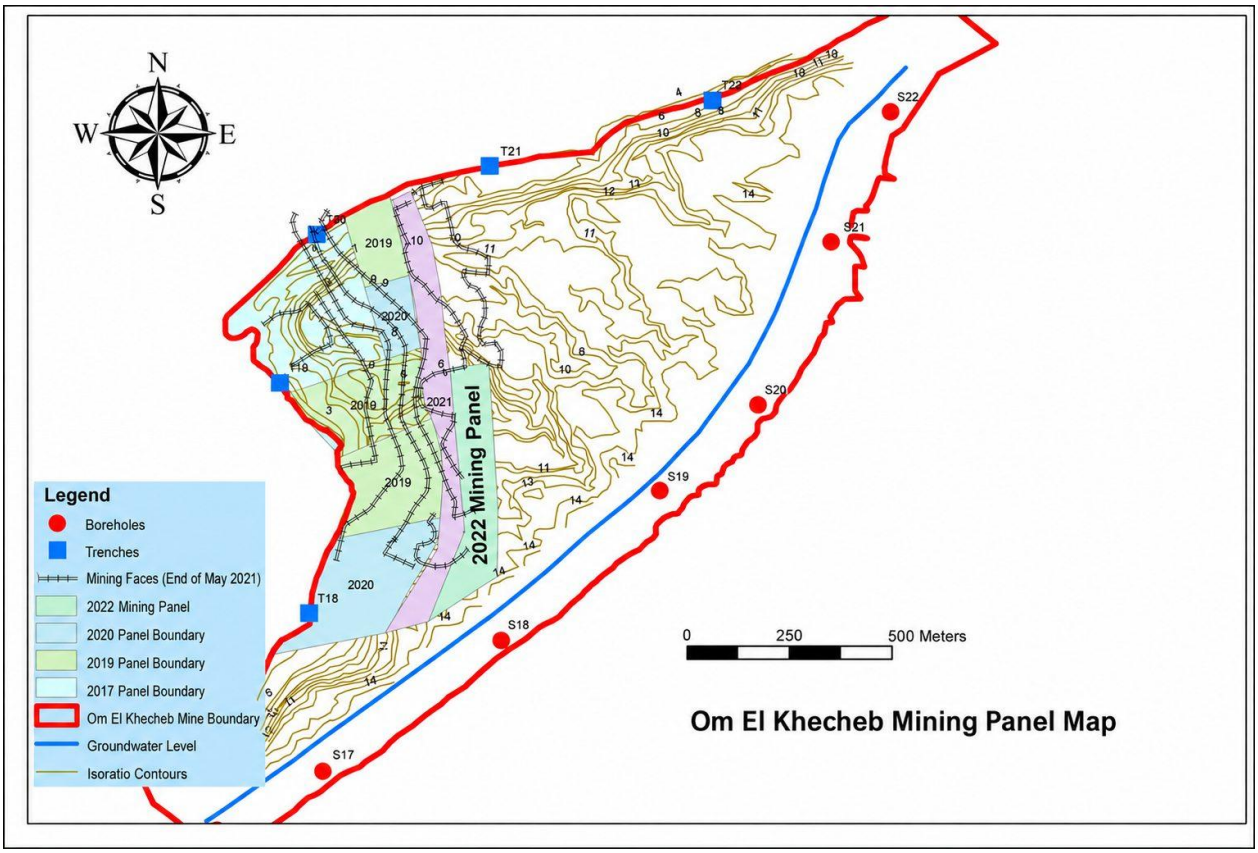


Fig. 17 Summary diagram illustrating the implications of the engineering-geological model for open-pit design and slope stability analysis in the eastern closure of Oum El Khecheb

The overburden geometry, characterised by the DTM and drillhole data, defines the pre-stripping requirements for phosphate access in the eastern sector and informs the scheduling of stripping operations relative to ore extraction. Conversely, sectors where the cap has been largely removed by erosion allow more direct access to the phosphate horizon and reduce pre-stripping requirements, but expose weathered marly material at surface. This trade-off between lower stripping cost and poorer ground conditions should be evaluated during the geotechnical campaign recommended above.

6 Conclusions

This study has presented a comprehensive integrated geological characterization of the eastern closure of the Oum El Khecheb phosphate open pit, addressing a sector of significant operational importance that had previously received insufficient systematic geological documentation. The principal findings can be summarized as follows.

The eastern closure is underlain by a coherent Paleocene–Eocene lithostratigraphic succession comprising the El Haria calcareous marls (basal substrate), The Thelja Formation (marly evaporite) the Chouabine Formation phosphorites (ore zone), the Metlaoui nummulitic limestones (cap rock), and gypsiferous marls and Quaternary cover (Burollet 1956; Sassi 1974; Galfati et al. 2010; Galai and Sliman 2019). The phosphate-bearing horizons thin and decrease in grade toward the periclinal nose, reflecting the distal depositional character of this sector relative to the main upwelling-driven phosphogenic locus in the basin.

Structural analysis documents the progressive eastward attenuation of the Oum El Khecheb anticline, with bedding dip decreasing from 30°–45° in the western sector to 10°–25° toward the eastern pericline; no part of the deposit behaves as a tabular body. This structural gradient has been formalized through the subdivision of the deposit into geometrically coherent intervals that serve as the fundamental units for reserve estimation and mine design. No major faults disrupt phosphate continuity across the eastern closure, although minor bench-scale discontinuities warrant consideration in detailed pit design and slope analysis.

The integration of drillhole data, field mapping, bench observations, topographic surveys, and production records into a three-dimensional geological model provides a reliable and internally consistent representation of the ore body geometry, overburden distribution, and rock mass character across the eastern closure. This model constitutes the essential geological input for slope stability assessment, resource evaluation, and long-term mine planning in this sector.

Looking ahead, the geological model developed here forms the foundation for several important follow-on investigations. Three-dimensional geostatistical resource evaluation, hydrogeological characterization of the rock mass to support dewatering design, and advanced slope stability analyses incorporating the specific geotechnical properties of the weak marly interbeds are identified as the most pressing priorities. Extending the integrated geological approach applied in this study to other closure sectors of the Oum El Khecheb pit, and to comparable deposits across the Gafsa–Metlaoui basin, would further contribute to the geological knowledge base underpinning sustainable phosphate production in Tunisia for further works on the kinematic of the Oum El Khecheb structure.

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Statements and Declarations

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Competing Interests

Mohamed Nejmaoui is head of the Oum El Khecheb open-pit operations at the Compagnie des Phosphates de Gafsa (CPG), which authorized access to the geological and operational data used in this study. The authors have no other financial or non-financial interests to disclose.

Author Contributions

Mohamed Nejmaoui: conceptualization, investigation, data curation, formal analysis, writing — original draft. Tarek Kormi: supervision, validation, writing, review and editing. Both authors read and approved the final manuscript.

Data Availability

The data underlying this study are the property of the Compagnie des Phosphates de Gafsa (CPG) and cannot be deposited in a public repository for reasons of commercial confidentiality. They are available from the corresponding author on reasonable request and with the written permission of CPG.

Ethics Approval

Not applicable. This study did not involve human participants, human data or animals.

Consent to Participate

Not applicable. This study did not involve human participants.

Consent to Publish

Not applicable. This study did not involve human participants, and the manuscript contains no data or images relating to an identifiable individual.

Clinical Trial Number

Not applicable. This study is not a clinical trial.

Use of Generative Artificial Intelligence

During the preparation of this work the authors used a generative artificial intelligence assistant for language editing only. The authors reviewed and edited the content as needed and take full responsibility for the content of the published article. No generative artificial intelligence tool was used to generate, analyse or interpret the geological, structural or statistical data reported here.