



Article Meteoric Water Incursion, Crude Oil Degradation and Calcite Cementation of an Upper Cretaceous Reservoir in the Zagros Foreland Basin (Kurdistan Region of Iraq)

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Abstract: Field observations, together with the results of gas chromatography–mass spectrometry (GC-MS) and stable carbon isotope analysis of bitumen, coupled with fluid inclusion microthermometry and stable isotope analyses of closely associated vug- and fracture-filling columnar calcite in the Upper Cretaceous Bekhme Formation, Kurdistan Region of Iraq, suggest that the degradation of crude oil was caused by the regional incursion of meteoric waters. This incursion, which is interpreted to have occurred during tectonic uplift during the Zagros Orogeny, is evidenced by: (i) the depletion of n-alkanes and acyclic isoprenoid alkanes (pristane and phytane) in the bitumen; (ii) low $\delta^{13}C_{VPDB}$ values (-8.5% to -3.9%) and $\delta^{18}O_{VPDB}$ values (-22.9% to -15.0%), with more radiogenic Sr isotopic ratios (0.70771–0.70772) compared to Cretaceous seawater; and (iii) low salinity and low temperatures (20 to 40 °C) in fluid inclusions of the columnar calcite. This study demonstrates that regional meteoric water incursion into sedimentary basins can be linked to crude oil degradation accompanied by calcite cementation events in carbonate reservoirs.

Keywords: meteoric water incursion; crude oil degradation; columnar calcite cementation; upper cretaceous; Kurdistan Region Iraq

1. Introduction

Heavy oil and solid bitumen in hydrocarbon reservoirs create barriers to fluid flow, causing porosity and permeability deterioration and, thus, serious production problems [1]. Undersaturated meteoric waters preferentially remove water-soluble compounds from oil, such as light aromatics (benzene and toluene) [2], which results in an increase of bitumen and heavy oil residues [3,4]. This process is known as water washing [5]. Moreover, aerobic bacteria introduced by meteoric waters have also been suggested to cause the biodegradation of crude oils [6,7]. Water washing and biodegradation may act independently or together [8], but current analytical techniques are not able to precisely recognize their separate roles in the degradation of crude oil [6,7,9]. Apart from the role of meteoric waters,



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). degassing of methane may also result in an enrichment of the asphaltene content in crude oil [10].

Heavy oils and solid bitumens with low API gravity (<27°) have frequently been encountered in recent discoveries and drilling activities in the Kurdistan Region of Iraq, but their origin is poorly understood [11]. It is not clear yet whether crude oil degradation and the formation of heavy oil is local or distributed across the entire Zagros Foreland Basin [7,11,12]. Heavy oil in several recent discoveries in the Bekhme Formation poses a serious challenge to the development of these oil fields in the region [11,13].

This study focuses on identifying the timing and origin of bitumen formation and the closely associated calcite cementation in the Upper Cretaceous Bekhme Formation at an outcrop in the Bekhme anticline in Iraqi Kurdistan. The Formation consists of dolostones containing vugs and fractures filled with coarse crystalline dolomite, calcite, and bitumen. This current study attempts to shed light on the degradation of hydrocarbons, generation of heavy oil, and the associated calcite cementation in the Upper Cretaceous Bekhme Formation and other equivalent reservoirs in the Zagros Foreland Basin.

2. Geological Setting

The study area in the Kurdistan Region of Iraq lies in the Bekhme anticline, which consists of various outcropping units ranging in age from Jurassic–Cretaceous to Miocene (Figures 1 and 2A, [14,15]). The Bekhme Formation belongs to the Upper Campanian–Maastrichtian cycle. This depositional cycle began with a widespread transgression covering all of what is now Iraq, which took place after the termination of the tectonic activities caused by the Middle Cretaceous Orogeny. The cycle also resulted in several formations that show considerable lithological changes both vertically and horizontally, representing shallow to deep marine deposits [16,17].



Figure 1. Geological map of northern Iraq (**A**) showing the distribution of the Bekhme Formation (green) and Bekhme Anticline (red line) in the Kurdistan Region (**B**) (after [14]).



Figure 2. (**A**) Chronostratigraphic column for the study area (after [15]); (**B**) sampling location in the Bekhme Gorge, Kurdistan Region of northern Iraq; (**C**) outcrop showing the thick bitumen seeping out of the Bekhme Formation.

The tectonic history of the region started by rifting in the Permo-Triassic, which evolved into a passive margin in the Middle Jurassic period and into an active margin in the Late Cretaceous period, owing to the onset of Arabia–Eurasia convergence and formation of the Zagros and Taurus orogenic belts [18–20]. A foreland basin developed during the Campanian–Maastrichtian period in northern Iraq along the Zagros margin, with a clastic depocenter represented by the Tanjero Formation, whereas the Bekhme

Formation represents an isolated carbonate platform developed within a clastic starved part of the basin [21]. The Bekhme Formation lies within the tectonostratigraphic mega sequence AP9 K170 [22], is relatively short-lived (29 my), and contains an important phase of plate boundary development [17]. The onset of plate boundary development is marked by the major mid-Cretaceous uplift, regression, and associated unconformity, which is recognized across the entire Arabian Plate [22]. The Bekhme Formation was deposited during the Maastrichtian sea-level rise (K 180 MFS of [22]) in the Campanian platform.

The studied Bekhme Formation outcrop is about 315 m in height and is located in the type locality of the formation at the Bekhme Gorge (latitude 36°41′45″; longitude 44°16′57″). The Bekhme Formation in the studied area comprises three units: upper, middle, and lower. The lower unit (10 m thick) is composed of limestones and breccias. The middle unit (94 m thick) comprises limestones containing rudest fragments that alternate with fore-reef shoal limestones (Figures 2 and 3). The upper unit is 211 m thick and is composed of bituminous dolostones and limestones [23].



Figure 3. (A–C) Field images showing bitumen accumulation and vertically arranged columnar calcite crystals (red arrows) occurring along a fracture and thrust surfaces in Bekhme Formation.

3. Samples and Methods

Bitumen samples were collected from an outcrop in the Bekhme Gorge near the type locality of the Bekhme Formation (Figures 1 and 2B, C). Bitumen occurs in vugs, where it engulfs saddle dolomite and equant calcite, and in large veins, where it engulfs columnar calcite. (Figure 3A–C). The bitumen samples were dissolved in dichloromethane and then deasphalted with *n*-hexane using 0.45 μ m PFTE filters. The dissolved sample was fractioned into saturates, aromatics, resins, and asphaltenes using the SARA method [4].

Carbon isotopic composition of whole bitumen and SARA fractions was performed using a Thermo Finnigan1112 elemental analyzer coupled to a Finnigan Mat Delta-C mass spectrometer. The reference materials were USGS-40 L-glutamic acid, IAEA-CH6 sucrose, IAEA-CH7 polyethylene, IAEA 600 caffeine, and acetanilide. The ¹³C/¹²C ratio is reported in " δ " notation, and δ ¹³C relative to VPDB (Vienna Pee Dee Belemnite) (Table 1). Precision of analysis was better than 0.1 per mil based on internal and international standards [24]. Saturated and aromatic hydrocarbons were analyzed by gas chromatography–mass spectrometry (GC-MS). The GC-MS analyses were performed on a Thermo Scientific Trace GC Ultra gas chromatograph with a DB-5 Agilent Technologies column (60 m × 0.25 mm i.d. × 0.1 mm film) coupled to an ITQ900 mass spectrometer. Samples (1 µL) were injected using a splitless injector heated at 280 °C, and helium was used as a carrier gas with a constant flow rate of 1 mL/min. The oven temperature was programmed to run from an initial temperature of 40 °C (held for 1 min) to a final temperature of 300 °C at 2 °C/min and then held at 300 °C for 60 min. The mass spectrometer was operated in selective ion monitoring (SIM) electron impact mode (electron input energy, 40 eV; source temperature, 200 °C).

Table 1. Isotopic values for whole bitumen and all SARA fractions.

Samples	δ ¹³ C _{VPDB} (‰)	Fraction
SM-1 BIT	-27.8	Whole bitumen
SM-1 ASP	-27.9	Asphaltenes
SM-1 RES	-27.8	Resins
SM-1 ARO	-27.8	Aromatics
SM-1 SAT	-27.9	Saturates

The following ions were monitored: m/z 57 for *n*-alkanes, m/z 191 for tricyclic terpanes and hopanes, m/z 217 for steranes, and m/z 231 for triaromatic steroids [10,25,26]. MSD chemstation software was used for the identification of the biomarkers. Individual components were identified by comparison of their retention times and mass spectra with published data [10,24,25]. Relative abundances of triterpanes and steranes were calculated by measuring peak heights in the m/z 191 and m/z 217 fragmentograms, respectively. The extraction procedure and GC-MS analyses were carried out at the Department of Mineralogy, Petrology, and Applied Geology, University of Barcelona.

Twenty-three samples of columnar calcite were subjected to carbon and oxygen isotope analyses at the School of Environment, University of Windsor. The samples were reacted with pure H₃PO₄ at 25 °C for 1 h, and isotope analyses were then carried out on a Thermo Finnigan Delta Plus mass spectrometer, the analytical precision of which was \pm 0.05‰. Isotopic values are given in δ (delta)-notation and reported in per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) [27].

The ⁸⁷Sr/⁸⁶Sr ratios were obtained from columnar calcite powders by leaching the samples in 0.2 N HCL for 24 h at room temperature. The isotopic measurements were performed using an automated Finnigan 261 mass spectrometer equipped with nine Faraday collectors. Correction for isotopic fractionation during the analyses was made by normalization to ⁸⁶Sr/⁸⁸Sr = 0.1194. The mean standard error of mass spectrometer performance was \pm 0.00003 for standard NBS-987. Fluid inclusion microthermometry of calcite was performed on two double-polished wafers. A petrographic examination of fluid inclusions was conducted in order to determine the origin (primary, secondary, pseudo-

secondary, or uncertain), composition ("aqueous" or "hydrocarbon"), and estimated liquid to vapor ratios.

4. Results

Coarse crystalline columnar calcite lines large fractures filled by bitumen (Figure 3A–C).

4.1. Composition of Bitumen

SARA results show small quantities of saturated and aromatic hydrocarbons (5% and 11%, respectively) and substantial amounts of heavy compounds (i.e., resins and asphaltenes, 7.9% and 66.6%, respectively, and a loss of 9.3%). The mass chromatograms of TIC (total ion current) (Figure 4A) and ion m/z 57 show an UCM (unresolved complex mixture) hump (Figure 4B) and the m/z 191 chromatogram (Figure 5) shows the distributions of terpanes (tricyclics and pentacyclics). The presence of C₂₄ tetracyclic terpane is noticeable. The quantity of trisnorneohopane (Ts) is extremely low, compared with trisnorhopane [™], and consequently, the calculated Ts/(Ts + Tm) ratio is low too (0.15) (Figure 5A). Hopanes are dominated by $C_{29}H$. C_{29} norhopane is, overall, more abundant than C_{30} hopane (Figure 5B), ($C_{29}H/C_{30}H$ ratio = 1.62) and the C_{35} homohopane shows a similar abundance as C_{34} homohopane. The steroids (m/z 217 ion) chromatograms (Figure 6) reveal that steranes and diasteranes are present in relatively high quantities in the saturated hydrocarbon fractions of the studied sample. The C_{27} to C_{29} diasteranes are also present in low concentrations. Low-molecular-weight steranes (e.g., C21 pregnane and C_{22} homopregnane) are present in high amounts and pregnane is more prominent than the homopregnane (Figure 6).



Figure 4. (A) Total ion current and (B) m/z 57 chromatograms of saturated hydrocarbons showing a strong biodegradation of *n*-alkanes and an important unresolved complex mixture (UCM).



Figure 5. Partially reconstructed chromatogram (m/z 191) displaying the tricyclic terpanes (**A**) and homohopanes (**B**) distributions in the extracted sample.



Figure 6. Partially reconstructed chromatogram (m/z 217) showing the low-molecule pregnanes, regular steranes, and diasterane distributions in the extracted sample.

The bitumen contains higher amounts of C₂₈-TA (20R, 20S) than C₂₇-TA (20R) and C₂₆-TA (20S) counterparts and the value of C₂₈-TA (20S + 20R)/(C₂₆-TA 20S + C₂₇-TA 20R) is equal 1.49 (Figure 7). The $\delta^{13}C_{VPDB}$ values of the whole fraction of bitumen vary between -27.9% and -27.8%.



Figure 7. Partially reconstructed chromatogram (m/z 231) displaying the triaromatic steroids distribution in the extracted sample.

4.2. δ18. O, ⁸⁷Sr/⁸⁶Sr Isotopes and Fluid Inclusions of Columnar Calcite

The vugs (mostly 5–15 cm across) and breccia fractures are filled by coarse crystalline saddle dolomite, equant calcite, and, less frequently, anhydrite. The thrust planes are lined with large crystals of columnar calcite (ca. 3–5 cm long and 1 cm across). These crystals are oriented perpendicular to the thrust plane surfaces.

Columnar calcite has low $\delta^{18}O_{VPDB}$ (-22.9‰ to -15.0‰), $\delta^{13}C_{VPDB}$ (-9.8‰ and -2.5‰), and ⁸⁷Sr/⁸⁶Sr ratios of 0.70771 to 0.70772 (Figures 8 and 9, [28,29]). Mansurbeg et al. [30] reported that: (i) saddle dolomite has narrow ranges of $\delta^{18}O_{VPDB}$ (-14.5‰ to -7.4‰), $\delta^{13}C_{VPDB}$ (-3.6‰ to +2.6‰), and Sr isotopic ratios (0.70774–0.70780), and (ii) vug/fracture-filling equant calcite cement, which engulfs saddle dolomite, displays wide ranges of $\delta^{13}C_{VPDB}$ (-10.5‰ to +2.1‰), $\delta^{18}O_{VPDB}$ (-19.2‰ to -4.8‰), and Sr isotopic ratios (0.70773–0.70796).

Fluid inclusions in the columnar calcite crystals are mostly single-phase, liquid type and range in size from about 7 to 25 μ m. Final ice melting temperatures (Tmice) (cf. [31]) suggest average salinity of 0.5 wt.% NaCl eq. Furthermore, Mansurbeg et al. [30] reported that the homogenization temperatures (Th) in vug-filling saddle dolomite are 80–120 °C and first ice melting temperatures (Te) are -38 °C to -42 °C. Measured Tmice points to the salinity of 17–22 wt.% NaCl eq. The Th in equant calcite ranges between about 60 °C and 100 °C and the Te between about -50 to -52 °C. Salinity derived from Tmice ranges from 14 to 18 wt.% NaCl eq.

UV light observations made on hydrothermal equant calcite in the Bekhme Formation showed the presence of oil-filled fluid inclusions with pale- to dull-yellow or orange fluorescence [30]. No oil-filled fluid inclusions were reported in any other cements, except for equant calcite [28], which is typical of oil with an API gravity of about 15–25° (cf. [32]).



Figure 8. Cross-plot of the carbon and oxygen isotopic values of columnar calcite. These values are lower than what would be expected for calcite that was precipitated in equilibrium with Cretaceous seawater, as indicated by the pink box [28]. Note the positive correlation between carbon and oxygen isotopic values of the columnar calcite if the three outliers with unusually low δ^{18} O values are removed.



Figure 9. Cross-plot of strontium and oxygen isotopes [29] of columnar calcite showing that Sr isotopic ratios of the columnar calcite are higher than the postulated range for Cretaceous seawater.

5. Discussion

5.1. Bulk Bitumen Composition: Clues to Its Origin

The low contents of saturate and aromatic hydrocarbons (5% and 11% respectively) and a large percentage of heavy compounds (resins and asphaltenes) indicate that bitumen consists of heavy or degraded oil [33]. The carbon isotopic values for saturate and aromatic hydrocarbons ($-27.8 \ \infty$) suggest a marine origin [34]. The low concentration of C₂₃ to C₂₉ tricyclic terpanes suggests a limited input of terrigenous organic material [35,36]. The presence of C₂₄ tetracyclic terpane is expected for carbonate/evaporitic depositional environments (e.g., [10,37]).

The UCM hump revealed by mass chromatograms of TIC and ion m/z 57 (Figure 4) provides clues to the biodegradation processes. The lack of *n*-alkanes and isoprenoids, which prevents the determination of the carbon preference index (CPI), as well as ratios of pristane $Pr/n-C_{17}$ and phytane $Ph/n-C_{18}$, is also interpreted be the result of biodegradation (e.g., [33]). The prominent peaks present in the TIC and ion m/z 57 are interpreted to represent terpane and sterane biomarkers, which are relatively resistant to biodegradation. The near-absence of tricyclic terpanes (represented only by the $C_{23/3}$) on the m/z 191 chromatogram (Figure 5) cannot be attributed to biodegradation because these compounds are very resistant to biodegradation [38,39].

The extremely small amounts of trisnorneohopane (Ts) compared to trisnorhopane TM and the Ts/(Ts + Tm) ratio (0.15) indicate low thermal maturity due to the lower thermal stability of C₂₇17 α (H)-22,29,30-trisnorhopTM(Tm) compared to that of C₂₇18 α (H)-22,29,30-trisnorneohopane (Ts). Nevertheless, the Tm and Ts contents are influenced by the degree of maturation, type of organic matter, and lithology (e.g., [40,41]. According to Peters et al. [10], oils from carbonate source rocks show much lower (< 0.25) ratios compared to those in shales deposited in anoxic environments (0.26–0.35).

This ratio is an indicator for the type of carbonate rock. Carbonates have less than 0.25, and shale more than 0.26. The ratio in the studied sample is 0.15, so the source rock was a carbonate rock.

The presence of hopanes, particularly $C_{29}H$ and the relative abundance of C_{29} norhopane compared to C_{30} hopane, ($C_{29}H/C_{30}H$ ratio of 1.62) are typical for carbonate-rich source rocks [42,43]. The presence of gammacerane (Figure 5) suggests the restricted environment with water column stratification during source rock deposition [10,41,44]. This interpretation is further supported by the domination of homohopanes by the C_{31} homohopane and its decrease with increasing carbon number (Figure 5). The similar amounts of C_{35} homohopane and C_{34} homohopane and the predominance of C_{29}/C_{30} and the C_{35}/C_{34} hopanes are related to carbonate (hypersaline) environments (e.g., [41,45].

There are relatively high amounts of steranes and diasteranes (Figure 6) in the saturated hydrocarbon fractions of the studied sample. The observed higher proportion of C_{29} compared with C_{27} and C_{28} regular steranes suggests a terrigenous organic matter contribution to the source rock [46,47]. However, partial biodegradation of C_{27} and C_{28} steranes cannot be ruled out and, consequently, the ratio C_{29} over C_{27} cannot be taken into account. However, the presence of C_{30} sterane is a characteristic of marine origin. The presence of both C_{30} sterane and low Ts/Tm ratios (<1) further suggest that these oils were probably derived from a carbonate source rock deposited in a reducing environment [48,49]. The low concentrations of C_{27} to C_{29} diasteranes compared to low-molecular-weight steranes, such as C_{21} pregnane and C_{22} homopregnane, and the more prominent pregnane than the homopregnane (Figure 6) further support sediments deposited under hypersaline conditions [50].

The small concentrations of aromatic hydrocarbons are attributed to biodegradation and probably water washing. Conversely, the presence of triaromatic hydrocarbons (TA) is due to high resistivity to biodegradation under most depositional and diagenetic conditions [51–53]. The presence of C_{20} and C_{21} components points to low-to-medium biodegradation [54]. Due to the co-elution of C_{26} -TA (R) with C_{27} -TA 20(S), four other isomers were used to differentiate homologue variations. There are higher amounts of C_{28} -TA (20R, 20S) than C_{27} -TA (20R) and C_{26} -TA (20S) counterparts and the value of C_{28} -TA (20S + 20R)/(C_{26} -TA 20S + C_{27} -TA 20R) is equal to 1.49 (Figure 7).

5.2. Origin of Columnar Calcite

The overall trend of positive correlation between $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values in the columnar calcite cement (Figure 8) indicates the input of ¹²C upon a decrease in $\delta^{18}O_{VSMOW}$ of the pore fluids. The latter isotopic trend might suggest a trend of increased incursion rates of meteoric waters (cf. [30,55]. The higher Sr isotopic ratios of the columnar calcite than the range for Cretaceous seawater (0.7073–0.7075; [29]; Figure 9) corroborates input of ⁸⁷Sr by the incursion of meteoric waters. The source of this elevated radiogenic Sr can be related to the input of ⁸⁷Sr from the circulation of meteoric waters in siliciclastic rocks [30].

Integrating field observations, burial history curve, stable isotope analyses, and fluid inclusion microthermometry allows us to decipher the origin of calcite that is closely associated with bitumen in the Upper Cretaceous Bekhme Formation. Evidence shows that bitumen postdates the crystallization of saddle dolomite [30], whereas the columnar calcite covers bitumen and field observations indicate that the bitumen is intermixed with equant calcite and fills the center of vugs and fractures.

The negative $\delta^{18}O_{VPDB}$ values (-22.9‰ to -15.0‰) and inferred temperatures (\leq 50 °C), coupled with low salinity (average 0.5 wt.% NaCl eq.) of the columnar calcite suggest precipitation from meteoric waters [30]. Using these oxygen isotopic values and near-surface temperatures (25–40 °C) (Figure 10), and the oxygen isotope fractionation equation between calcite and water [56], the $\delta^{18}O_{VSMOW}$ of the meteoric water is inferred to range from -12.1‰ to -22.4‰. However, for poorly understood reasons, these values are too low for the reported meteoric waters at the paleo-latitude of the basin, which are similar to present-day latitudes of $\delta^{18}O_{VSMOW}$ of around -5‰, e.g., [57]. The $\delta^{18}O_{VPDB}$ of calcite is instead -7.2‰. However, local factors, such as relief and seasonal variations, may affect $\delta^{18}O$ values (cf. [30,57]).



Figure 10. Cross-plot of homogenization temperatures versus oxygen isotopic values of calcite and dolomite. Note that saddle dolomite, equant calcite, and host dolostones have overlapping values, presumably owing to the genetic link between these carbonates, which is the flux of hydrothermal brines [30]. The negative oxygen isotopic values combined with the very low salinity of fluids responsible for the precipitation of columnar calcite suggest a meteoric origin.

The wide range of $\delta^{13}C_{VPDB}$ values (-9.8‰ and -2.5‰) of the columnar calcite cement is attributed to variations in the input of ¹²C-enriched dissolved carbon derived from the degradation of crude oil $\delta^{13}C_{VPDB}$ values <-20‰; [58–60]), as well as input of ¹³C from dissolution of Cretaceous marine carbonates. Therefore, calcite with higher $\delta^{13}C_{VPDB}$ values was likely formed during early stages of crude oil degradation, unlike calcite with lower $\delta^{13}C_{VPDB}$ values.

The estimated API of the trapped hydrocarbons within the equant calcite (15–25° API; [30], which is paragenetically earlier than the columnar calcite (Figure 11), is higher than the measured API (10–17°; [61]) in the present-day oil, which further supports the role of meteoric water biodegradation.

The burial history curve for the study area (Figure 12; [11,62]) shows a significant uplift/erosion of the Bekhme Formation in the final stages of Zagros Orogeny, bringing the successions close to the basin margin (i.e., with increased hydraulic head that facilitated meteoric water incursion). The presence of the columnar calcite (Figure 3A–C) along the thrust walls suggests that cool (<50 °C), low-salinity (<0.5 wt.% NaCl eq.) meteoric-water flux, coupled with oil degradation and columnar calcite cementation, occurred simultaneously. Oil degradation is a process that generally increases carbonate alkalinity and, hence, promotes carbonate precipitation, as evidenced by the isotopically light δ^{13} C isotopic composition of this calcite [30,60].

Burial/Tectonic		Zagros Orogeny					
Events		Strike-Slip faulting			5	Normal fau	ılting
Diagenetic	Near-surface diagenesis	Pre-to syn-folding			Post-folding		
Minerals/Events	80Ma	Hyd 30Ma	rothermal fluids	20Ma	Meteoric P	ercolation	0Ma
	25°C 60°C	120°C		75°C			
Equant calcite							
Columnar calcite							
Oil migration							
Oil degradation							

Figure 11. General paragenetic sequence reconstructed for the Bekhme Formation in relation to burial and orogenic events.



Figure 12. Burial history curve of the study area shows a significant uplift/erosion of the Bekhme Formation in the Upper Cretaceous period (modified after [11,15,62]).

6. Conclusions

Integration of gas chromatography, fluid inclusion petrography and microthermometry, carbon, oxygen, and strontium isotope data has provided important insights into the role of meteoric water incursion in crude oil degradation in Cretaceous carbonate reservoirs in the Kurdistan Region of Iraq. The main conclusions derived from this study include:

- Alteration of hydrocarbons took place via biodegradation and water washing that affected aromatics and steranes. The organic matter precursor was deposited in a restricted carbonatic/evaporitic environment.
- The depletion of *n*-alkanes and acyclic isoprenoid (pristane and phytane) confirm that biodegradation affected the hydrocarbons. The prominent peaks are mostly terpane and sterane biomarkers, which are more resistant to the biodegradation. The presence of triaromatic steroid (TAS) hydrocarbons in the analyzed sample is evidence of moderate degradation. Moreover, the presence of C_{26–28} homologues and the C₂₀ and C₂₁ components of TAS are consistent with the interpretation of limited biodegradation of the hydrocarbons.
- High quantities of steranes and diasteranes in the saturated hydrocarbon fraction and a higher proportion of C₂₉ compared with C₂₇ and C₂₈ regular steranes are attributed to terrigenous organic matter contribution.
- The negative oxygen and carbon stable isotopes, non-radiogenic Sr isotopic ratios, low salinity, and low temperatures in fluid inclusions of the columnar calcite suggest that calcite cementation occurred simultaneously with oil degradation, which acted as the source of ¹²C in dissolved carbon needed for calcite precipitation.

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