PALEOClimATE CONTROL ON THE DIAGE netic HiSTORY AND SEQUENCE STRATIGRAPHY OF THE UPPER SARvAK FORMATION, DEZFUL EMBAYMENT, SW IRAN

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ABSTRACT
Integrated diagenetic analyses within a sequence stratigraphic framework were carried out on upper Cretaceous Sarvak carbonate reservoirs in Ahvaz oilfield in the Dezful Embayment, SW Iran. Diagenetic studies indicate periods of subaerial exposure with different intensities and durations in the upper Sarvak carbonates producing karstified profiles, dissolution collapse breccias, and thick bauxitic-lateritic horizons. Sequence stratigraphic interpretations show that the tectonic evolution of the NE of the Arabian Plate (Zagros Basin) during Cenomanian-Turonian times shaped the diagenetic features, and strongly influenced reservoir formation.

Keywords: Sarvak Formation, Diagenetic, Sequence Stratigraphy, Climate, Dezful Embayment

INTRODUCTION
Integrated diagenetic analyses within a sequence stratigraphic framework are essential prerequisites for any systematic reservoir characterization study (Moore, 2001; Schlager, 2005; Roger, 2006; Lucia, 2007; Ahr, 2008). Generally, sedimentary facies control primary poroperm distribution in carbonate reservoirs (Schlager, 2005). In the absence of significant diagenesis, reservoir parameters are mostly controlled by individual facies characteristics (micro-scale) and the distribution of sedimentary environments (macro-scale) (e.g., Ahr, 2008). Additionally, diagenesis is the main factor controlling reservoir quality in most carbonate reservoirs of the world (James and Choquette, 1984; Ehrenberg, 2006; Ehrenberg et al., 2008). Nonetheless, many of the diagenetic path ways are controlled directly (early diagenetic features) or indirectly (late diagenetic processes) by primary (facies) characteristics of sediments (that is facies controlled diagenesis). Meteoric diagenetic processes are the essential factors governing the reservoir quality of unconformity related carbonate reservoirs (Immenhauser et al., 2000; Moore, 2001; Weidlich, 2010; Reinhold and Kaufmann, 2010). Depending on several factors, notably climatic conditions, duration of exposure and mineralogy, these processes may improve or destroy reservoir quality (Mazzullo and Chilingarian, 1992; Weidlich, 2010). Global, regional, and local relative sea level changes together with tectonic activities are the main factors shaping sequences (Sharland et al., 2001; Hofmann and Keller, 2006; Razin et al., 2010). Correlation of diagenetic features within a sequence stratigraphic framework has resulted in the generation of geological models for carbonate reservoirs that can be used in reservoir simulations (Roger, 2006). The Sarvak Formation in SW Iran has been the subject of several studies dealing with facies and paleo environments, diagenetic features, sequence stratigraphy, and reservoir quality of this second, most important hydrocarbon reservoir in Iran (e.g., Taghavi et al., 2006; Ghabeishavi et al., 2010; Hajikazemi et al., 2012; Razin et al., 2010; Rahimpour-Bonab et al., 2012a, b). The main target of this research is to investigate the control of paleoclimate on the diagenetic history and sequence stratigraphy of the upper Sarvak Formation, Dezful Embayment in SW Iran, with coming from one well from Ahvaz oilfield (Figure 1).

MATERIALS AND METHODS
For sedimentological analysis and interpretations, about 750 m of core from one exploratory or appraisal well drilled in Ahvaz oilfield, located in Dezful Embayment were examined in detail to describe the various facies and diagenetic features. In addition, diagenetic studies and microscopic image analyses on
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250 thin-sections were carried out. On the basis of statistical analysis of the facies associations and their frequencies in the studied well, their approximate positions in the depositional model were determined. Results of facies analysis (e.g., vertical facies variation), diagenetic study were used for determination of the third order sequence in the studied interval. Additionally, these third order sequences were correlated with the other studies in Iran and neighboring areas.

![Location map of the Ahvaz oilfield in the Dezful Embayment of southwest Iran. The main geological and structural subdivisions of SW part of Iran are also shown and the location of the Dezful Embayment in this framework is marked](image)

**Figure 1**: Location map of the Ahvaz oilfield in the Dezful Embayment of southwest Iran. The main geological and structural subdivisions of SW part of Iran are also shown and the location of the Dezful Embayment in this framework is marked

**Paleoclimate and Paleogeography**

The upper Cretaceous (Cenomanian–Turonian; 98–92 Ma) is generally described as a warm period across the world and in the Middle East (Huber et al., 2002; Hay, 2008; Keller et al., 2008). At this time, the NE margin of the Arabian Plate (i.e., Zagros Basin) was located in the northern hemisphere close to the equator (Setudehnia, 1978; Sharland et al., 2001; Ziegler, 2001; Huber et al., 2002) (Figure 2). Thus, the upper Cretaceous Sarvak platform was under the domination of a warm and humid tropical climate with heavy rainfall. Tectonically, in the Neotethys, the upper Cretaceous is the beginning of oceanic crust subduction beneath central Iran and Oman (Glennie, 2000; Sepehr and Cosgrove, 2004; Bordenave and Hegre, 2005; Heydari, 2008). Evidence for this event is recorded by ophiolites obducted on to the continental crust in the Zagros suture zone (Neyriz and Kermanshah) and Oman Mountains (Motiei, 1993; Alsharhan and Nairn, 1993; Sharland et al., 2001) (Figure 2). At this time, the NE margin of the Arabian Plate changed from a passive continental margin in to an active tectonic one (Sepehr and Cosgrove, 2004; Alavi, 2004, 2007). Reactivation of basement faults along with halokinetic movements, related to the Hormoz salt series, marked the upper Cretaceous as one of the most tectonically active periods in the geological history of the Middle East (Ahmadhadi et al., 2007; Motamedi et al., 2011).
These tectonic activities led to the generation of multiple paleohighs in different parts of the region including SW Iran and the Dezful Embayment (Figure 2). Moreover, the presence of these paleohighs resulted in great variations diagenesis of contemporaneous carbonate formations (Sepehr and Cosgrove, 2004; Alavi, 2004, 2007; Rahimpour-Bonab et al., 2012a). The presence of several paleohighs is recorded on seismic lines in SW Iran. Eustatic sea level fluctuations from the Albian to Turonian (Figure 2c), accompanied by the humid climate, exerted strong controls over the reservoir quality by recurring subaerial exposure and formation of disconformities in the sedimentary record of the Middle East and SW Iran (Van et al., 1996; Sharland et al., 2001; Immenhauser et al., 2000; Sadooni and Aqrawi, 2000; Razin et al., 2010; Hajikazemi et al., 2010, 2012; Rahimpour-Bonab et al., 2012a). During this time, two and locally three high-order falls have been recorded at sea levels (marked as 1, 2, and 3 in Figure 2c).

Figure 2: A Stratigraphy of the Cretaceous successions in the Dezful Embayment. b Generalized chronostratigraphy of the Cretaceous successions in the Zagros Basin (SW Iran), Kuwait, and Saudi Arabia. Maximum flooding surfaces (MFS) and tectonostratigraphic megasequences (TMS) of (Sharland et al., 2001) are also shown. Preservation of the main flooding surfaces (their development in different parts of the Middle East) is described by 1, 2, and 3 numbers for high, medium, and low preservation, respectively. c Stratigraphy of the Bangestan group in the Ahvaz

However, an integration of sea level fluctuations with tectonic activities has been considered as the main controls. Accordingly, meteoric diagenesis (including development of karstic and microkarstic networks, collapse brecciation and bauxite laterite horizons) related to various disconformities, altered the reservoir quality of the Sarvak Formation and its equivalents in the surround dingareas (Aqrawi et al., 1998; Taghavi et al., 2006; Beiranvand et al., 2007; Ehrenberg et al., 2008; Volery et al., 2009; Ehrenberg et al., 2008; Volery et al., 2009; Hajikazemi et al., 2010; Rahimpour-Bonab et al., 2012a).

So far, the presence of three regional (mid Cenomanian and mid Turonian) and local (Cenomanian– Turonia boundary) unconformities has been substantiated at various subsurface sections of the Sarvak
Formation in different parts of the Dezful Embayment (Van et al., 2001; Rahimpour-Bonab et al., 2012a). The Sarvak Formation in the studied oilfield (Figure 1b) encompasses two unconformities (Figure 2c).

**Stratigraphy**

The Dezful Embayment of southwest Iran (Figure 1) is one of the most prolific hydrocarbon provinces of the world. Several giant and supergiant oilfields are located in this province that produce oil (and gas, with less importance) mainly from the Mesozoic Khami Group (Fahlryan and Dariyan Formations) and Bangestan Group (Sarvak and Ilam Formations) and Cenozoic Asmari Formation (Figure 2a). The Sarvak Formation (late Albian–middle Turonian) of the Bangestan reservoirs is the second most important reservoir succession (after the Oligo-Miocene Asmari Formation) in the Zagros Basin (Motiei, 1993; Figure 2). Lithologically, it is composed mainly of limestones that are dolomitic in parts. In most parts of the Dezful Embayment (and other neighboring areas in the Fars province and the Persian Gulf basin), the lower parts of the Sarvak Formation are composed of pelagic, argillaceous limestone that has a lower reservoir quality than its upper parts. In these areas, some thin intervals of marl and shale (mostly less than 10 m thickness) are also present (Motiei, 1993). The upper part of the Sarvak shows higher reservoir quality due to the effects of the above-noted unconformities (Taghavi et al., 2006; Hajikazemi et al., 2010; Rahimpour-Bonab et al., 2012a, b).

For this reason, most of the exploratory and appraisal wells in the Dezful Embayment oilfields have only drilled the upper part of this formation (Figure 1). The studied interval is equivalent to the Mishrif Formation in Iraq, Natih Formation in Oman, Mishrif, Ahmadi and Rumaila Formations in UAE and Kuwait (Figure 2b), and Derder Formation in SE Turkey. Seemingly, all these units were deposited on a ramp-like carbonate platform on the NE margin of the Arabian Plate. In its type section, the Sarvak Formation lies upon the Kazhdumi Formation with a transitional contact and is overlain by shale and marl of the Gurpi Formation with a sharp contact (Motiei, 1993). However, in several parts of the Dezful Embayment (including studied oilfield) carbonates of the Ilam Formation rest upon the Sarvak with a disconformable contact (Figure 2a, c). Depending on the presence and numbers of unconformities, the Sarvak Formation can be divided in to two (lower and upper; where only one disconformable surface is present) or locally three parts (lower, middle, and upper, where two important unconformities are present) (Rahimpour-Bonab et al., 2012a) (Figure 2c).

This study is focused on the Sarvak interval above the local C-T unconformity, which includes its middle and upper parts. During the early Cretaceous, the general configuration of the NE margin of the Arabian Plate changed from an active tectonic margin, including shallow shelves and intrashelf basins (developed during the Jurassic), in to a passive margin ramp system of low relief (e.g., Setudehnia, 1978; Murris, 1980; Motiei, 1993; Ziegler, 2001; Sharland et al., 2001; Hollis, 2011). During the Cenomanian–Turonian, sedimentation rates varied considerably, from high deposition rates (e.g., in NE Persian Gulf), leading to accumulation of thick successions (e.g., in type section of the Sarvak Formation in the Bangestan Mountain. The variable thicknesses are evident from the isopach maps of the upper Cretaceous for the sedimentary basin (Figure 3b; Motiei, 1993).

The variations in thickness suggest a period of instability, characterized by reactivation of basement block faults in the Dezful Embayment and active salt tectonism in the Persian Gulf. Thickness differences within the Sarvak Formation could also be ascribed to erosion at the disconformable surfaces (discussed in this study) or variable subsidence rates in different parts of the depositional environment.

**Diagenesis**

Considering the climatic conditions governing the upper Cretaceous carbonate platforms in the Middle East region (warm and humid tropical climate), a diagenetic history could be envisaged for these productive carbonate intervals. Here, diagenetic processes affected Sarvak carbonates and forged their present reservoir quality are interpreted in the context of geological history (climate) of this basin. The most important diagenetic processes that affected the upper Sarvak reservoir carbonates are extensive meteoric dissolution and karstification, karst related brecciation, and the development of bauxitic-lateralitic horizons.
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Dissolution and Karstification

Metoeoric dissolution is very common in the upper part of Sarvak Formation in the form of microkarstic networks on a microscopic scale, and dissolution cavities and channels on a macro-scale. Micro karstic networks comprise separate, fabric-selective vugs and touching, non-fabric selective vugs that are empty or partially to completely filled by various types of meteoric or burial cements (Figure 4). Two phases of dissolution can be recognized:

a) Extensive fabric-selective vugs formed just after deposition before the sediments were completely lithified. This eogenetic dissolution is limited to metastable (aragonite and high magnesium calcite) bioclasts (e.g., rudistid debris and other bivalves) (Figure 4a, c) and took place in an open diagenetic system (high water/rock ratio) to create biomoldic.

b) Porosity with separate vugs. Later, these were mostly cemented by meteoric (phreatic) or burial cements (Figure 4d, e), although some of these vugs are fully to partially preserved and form high reservoir quality units, especially where they are connected through microfractures. (b) Touching non-fabric selective vuggy systems are very common below two main unconformities: the C-T boundary and mid Turonian unconformities (Figure 4b). In shallow to deep burial environments, this phase of dissolution and brecciation occurred after sediment lithification and so was non-fabric selective. This process affected all components including the bioclasts, non-skeletal grains, cements, and matrix, and gave rise to the creation of touching and separate vugs, and moldic porosities.

Dissolution – Collapse Brecciation and Paleosoil Formation

Collapse of dissolution features (cavities, channels, and vugs) and their filling by breccias and internal sediments (e.g., vadose silts), reducing reservoir quality just below diagenetic surfaces (Khalaf, 2011). In such locations, long-term subaerial exposure of Sarvak carbonates occurred from the mid Turonian to late Coniacian (approximately 4–6 million years); (Van et al., 2001; Hajikazemi et al., 2010, 2012) and caused a stratigraphic hiatus (Motiei, 1993). Extensive bauxitic-lateritic horizons together with collapse breccias (Figure 5d) are the main features of this long-term exposure (Figure 5d, e). In some areas in western and southwest Iran, these lateritic deposits are mineral targets and are under exploitation. Marine, meteoric, and burial calcite cementation (Figure 4d–f), dolomitization (Figure 5a, f), silicification (Figure 5b), sulphide mineralization (Figure 5c) and Stylolites (Figure 5f) are other important diagenetic features of the Sarvak Formation in the studied well that also affected reservoir quality. Some of the main diagenetic features recorded in core samples below the diagenetically altered surfaces in the studied well in Alhav oilfield.

Diagenetic History (Paragetic Sequence)
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2007) to reconstruct the paragenetic sequences. The intense circulation of meteoric fluids under the humid tropical climate caused severe diagenesis (eogenetic meteoric diagenesis), notably fabric selective dissolution and metastable mineral stabilization in the uppermost 45 m of the upper Sarvak (Figure 7).

In view of heavy rainfall, meteoric alteration of these carbonates extended to most parts of the upper Sarvak Formation, forming extensive karst features and generating exceptional reservoir quality (e.g., Taghavi et al., 2006; Rahimpour-Bonab et al., 2012b). A relative sea level rise in the early Turonian re-established sedimentation on the carbonate ramp to deposit the upper Sarvak Formation from early to mid Turonian. Consequently, the uppermost part of the upper Sarvak, located below the intra formational C-T disconformity, has experienced meteoric diagenesis during eogenetic and then telogenetic phases. The telogenetic event occurred after upper Sarvak deposition and uplift (due to the tectonic events and sea level fall) during the mid Turonian. This mid Turonian regional uplift formed a basin wide disconformity (Setudehnia, 1978; Alsharhan and Nairn, 1993; Sharland et al., 2001), which has been described in outcrops and subsurface sections from many areas on the Arabian Platform and Zagros Basin (Sadooni, 2005; Taghavi et al., 2006; Razin et al., 2010; Hajikazemi et al., 2010, 2012). In addition, from a geophysical study of the Sirri Oilfield in the Persian Gulf, (Farzadi and Hesthmer, 2007) demonstrated that the carbonates of the Sarvak Formation were affected by periodic subaerial exposure. This exposure event brought about extensive dissolution leading to the formation of collapse breccias, causing immense reservoir quality enhancement. In these locations, only one important disconformity is recorded, at the top of the upper Sarvak, and this coincides with the basin wide mid Turonian sea level fall and platform exposure. Eogenetic meteoric diagenesis during this emergence in the mid Turonian led to the development of microkarstic networks in the upper Sarvak in some places. Meteoric diagenetic features, such as intense dissolution, solution-collapse brecciation and meteoric cementation along with development of palaeosol horizons are recorded beneath this disconformity in the studied wells. Samples collected below this disconformity have heavily depleted δ18O (−4‰ to −6‰ PDB) and δ13C (−1‰ to −8‰ PDB) values (Figure 6).

Sequence Stratigraphy

For this study, a sequence stratigraphic framework was constructed for the upper part of the Sarvak Formation (the late Cenomanian to mid Turonian part) in the Dezful Embayment, incorporating all the data from facies and biostratigraphic analyses, and diagenetic features, notably horizons of subaerial exposure, paleokarstic features and bauxitic lateritic horizons. Sequence boundaries were identified by evidence for rapid changes in facies and distinct diagenetic effects related to sea level fall. These analyses resulted in recognition of two third order sequences in the late Cenomanian to mid Turonian interval of the Sarvak Formation in the Ahvaz oilfield (Figure 6).

Sequence 1(Sq1)

This sequence includes a relatively thick transgressive system tract (TST) to 46 m thickness in the studied wells. It is composed of mud to grain dominated facies (mainly mudstone and wackestone) shows deepening upward characteristics, including increase in the planktic faunal content, and an upward decrease in energy level that is reflected in the facies properties (Figure 6). The MFS is identified on the basis of such characteristics and represents the deepest facies in this sequence (outer ramp and basinal facies). The highstand systems tract (HST) comprises alternations of reefal debris (from local patch reefs) and shallow marine (lagoon to mid ramp) facies. In studied wells, the uppermost part of this sequence consists of rudist debris packstone floatstone of a fore reef (talus) environment. The sequence boundary (Disc. 2; Figure 6) Extensive meteoric dissolution and karstification together with Fe oxide staining are the main diagenetic features of the sequence boundary. About 47 m thick interval below the SB in the studied wells is affected by these alterations.
Figure 4: Photomicrographs of the two phases of dissolution (a, b, and a, c), which occurred in the first stage of the paragenetic sequence of the Sarvak carbonates and caused extensive dissolution in the unconsolidated sediments (eogenetic). The second dissolution phase (non-fabric selective in a telogenetic meteoric environment; b) affected the uppermost part of the middle Sarvak Formation and occurred after sediment consolidation. c) and cementation (d, e, and f) that affected Sarvak carbonates. These dissolution phases include fabric-selective meteoric dissolution.

Figure 5: Main diagenetic features that overprinted the Sarvak carbonates in the studied oilfield. These include dolomitization (a), silicification (b), pyritization (c), micro-scale brecciation (d), Fe-oxide staining (e), stylolitization (f).
Figure 6: Petrographic evidence of two major disconformity surfaces recognized in study well. The main diagenetic features that recorded below the disconformable surfaces in the Ahvaz Oilfield. δ13C and δ18O compositions of this well are also shown. Depletion in both δ18O and δ13C is recorded below the palaeo exposure surfaces in the studied wells. These depleted values are interpreted to be due to meteoric water/rock reactions associated with subaerial exposure.

Figure 7: Paragenetic sequence of diagenetic events that overprinted the Sarvak carbonates. For upper Sarvak, the sequence of diagenetic events occurred in marine, eogenetic meteoric, shallow burial, telogenic meteoric, and, finally, deep burial stages.
Sequence 2 (SQ2)
The thickness of this sequence shows great to 115 m, which are related to the foresaid tectonic activities coupled with sea level fluctuations during the Turonian. The thickest intervals of this sequence are recorded in studied wells, respectively. It is the result of long term subaerial exposure and erosion of the upper parts of the Sarvak Formation in the mid Turonian. Evidence for the recognition of its TST is similar to that of the older sequence and its MFS indicates low energy conditions, high ratio of planktic to benthic faunal assemblages. The HST comprises alternating talus, shoal (less important), and shallow marine facies, passing upward in to lagoonal and patch reef facies. The upper most interval of this system tract (top 45m in the studied wells) shows leaching features such as large scale vuggy porosity(touching and separate vugs) and Fe oxide staining (bauxitic lateritic horizons) that are used to detect the sequence boundary. In view of the relationships between the sequence components (i.e., sequence surfaces and systems tracts) and reservoir parameters, there is an incremental trend in poroperm values in the HST, which reaches its maximum below the sequence boundaries in studied wells. To construct a time frame work for sequence correlations, the earlier biostratigraphic analysis of the other oilfield was used. These third order sequences can be correlated with other stratigraphic schemes from surrounding areas in SW Iran (Razin et al., 2010) and the Middle East region (e.g., Van et al., 1996; Soroka et al., 2005). In Figure 8 the recognized sequences are well correlated with the sequence stratigraphic analyses in the neighboring areas (Van et al., 1996; Soroka et al., 2005; Razin et al., 2010). In the Padena section of southwest Iran (Razin et al., 2010) and the Natih Formation of Oman (Van et al., 2002) two third order sequences are introduced. In our study, no evidence is recorded for this sequence boundary and so only one third order sequence is presented in the late Cenomanian to early Turonian part of the Sarvak Formation in studied wells. Is recorded in the Turonian interval, which is a result from their location (far from the above mentioned paleohighs). This resulted in reduced effects of subaerial exposure and erosion on the upper Sarvak Formation. Besides, in such situations, more accommodation space was available for carbonate deposition. Both of these factors resulted in thicker sequences. In some parts of southwest Iran and surrounding areas (i.e., Burchette, 1993 in Dubai, UAE; Figure 8), the C-T disconformity is not recorded and mid Turonian is the only disconformity in the upper Sarvak and its equivalents. This clear correlation over the vast area of southwest Iran and the Arabian Platform indicates the role of eustatic sea level fluctuations in the formation of depositional sequences during this time interval. Thus, coupled with the sea level fluctuations, tectonic activities exerted an important control on the local scale.

RESULTS AND DISCUSSION
Integrated diagenetic and sequence stratigraphic analyses of the upper Sarvak Formation (late Cenomanian to mid Turonian) in studied wells in Ahvaz oilfield located in SW Iran in the Dezful Embayment were undertaken to determine the climatic control on its characteristics. Extensive meteoric dissolution features (karstification), dissolution collapse breccias, and lateritic horizons within the Sarvak carbonates were related to recurring subaerial exposure of its upper part in the studied oilfield. In Ahwaz oilfield the absence of local paleohighs resulted in a less complicated diagenetic history, a passage from Seemingly, marine to eogenetic meteoric and then to shallow and deep burial environments. Variations in the diagenetic histories of the upper Sarvak carbonates in different parts of the Dezful Embayment have led to issues with understanding the reservoir characterization. Sequence stratigraphic analysis using depositional facies variations, diagenetic patterns, well log data, and biostratigraphy has allowed the recognition of Third order sequences in the upper part of the Sarvak Formation in the described wells. As a result of recurring subaerial exposure of Sarvak carbonates under the humid tropical climate, several (two and locally three) disconformities are recorded within its middle and upper parts, from mid Cenomanian to mid Turonian strata. Sequence stratigraphic correlations indicate considerable heterogeneities in the sequence thicknesses as a result of reactivation of basement blocks and Passive NE margin of the Arabian Plate became an active margin. Results of this study provided a geological based model(diagenetic models in a sequence stratigraphic framework) that can be used as a basis for ongoing reservoir modeling targets in the basin (regional) and field scales.
Figure 8: Correlation of third order sequences distinguished in the subsurface sections of the Dezful Embayment with other studies in the Zagros Basin and Arabian Platform. C-T and Mid-Turonian unconformities, which had a considerable impact on the reservoir quality of the Sarvak Formation (and its equivalents on Arabian Platform) are also shown.

Understanding the geological controls on the distribution of reservoir quality parameters in the mid Cretaceous these paleostructures existed from earlier times (Paleozoic and Mesozoic) and were reactivated by basement faults and halokinetic carbonate reservoirs of the Dezful Embayment is a critical
step in Sarvak reservoir simulation. Moreover, in this study, the role of paleoclimatic conditions as the main control on the quality of the carbonate reservoirs, are elaborated.

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