Sequence stratigraphy of the Late Cretaceous–Paleocene Gurpi Formation in southwest Iran

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ABSTRACT

Facies associations, microplanktonic diversity, palynofacies variations, geochemical data, and natural gamma-ray logs were analyzed from the Danial and Gurpi sections of the Campanian–Selandian Gurpi Formation in the Zagros Mountains, southwest Iran. The biostratigraphic data indicate that deposition across the Cretaceous/Paleogene boundary was continuous in the Danial Section. In contrast, a minor stratigraphic break seems to be present in the Gurpi Section, where several planktonic foraminiferal subzones are not identified. Nine depositional sequences were interpreted and correlated between the two sections. They are apparently of great lateral extent because they closely correlate to the global sea-level cycles. The Maastrichtian maximum flooding surface MFS K180 (68 Ma) of the Arabian Plate was also identified. Detailed palynofacies analysis, integrated with standard tropical/subtropical planktonic foraminifera, indicate warm Neo-Tethyan upper-bathyal to middle-shelf depositional environments for the Gurpi Formation.

INTRODUCTION

The Upper Cretaceous–Paleocene Gurpi Formation consists of deep-marine shales, marls and argillaceous lime mudstones that crop out in the Zagros Mountains, southwest Iran (Figure 1). The petroleum geology, stratigraphy and sedimentology of the formation have been presented in several papers (e.g. James and Wynd, 1965; Wynd, 1965; Sampo, 1969; Setudehnia, 1972, 1978; Stoneley, 1974, 1990; Motiei, 2003; Ghasemi-Nejad et al., 2006; Darvishzad et al., 2007). In contrast to previous studies, this paper seeks to integrate the biostratigraphy and facies analysis of the formation in a chrono- and sequence-stratigraphic framework. It is the third of a series that include Beiranvand and Ghasemi-Nejad (2013) and Beiranvand et al. (2013).

In the first paper, Beiranvand and Ghasemi-Nejad (2013) documented the high-resolution planktonic foraminiferal biostratigraphy of the Gurpi Formation in the Danial Section, located on the Payun Anticline, northeast Izeh in Iran (Figure 1). The study was focused on a 15 m stratigraphic interval that spans the Cretaceous/Paleogene boundary (K/Pg; see Table 1 for abbreviations), traditionally referred to as the Cretaceous/Tertiary boundary (KTB). This boundary is recognized as a major regional unconformity, referred to as the “pre-Cenozoic” or “base Tertiary” unconformity in the Arabian Plate (e.g. Sharland et al., 2001). In the Danial Section, however, a complete succession was shown to cross the boundary as evident by the occurrence of the uppermost Cretaceous Plummerita hantkeninoides Taxon-range Zone (TRZ), and lowermost Paleocene Guembelitria cretacea (P0) and Parvularugoglobigerina eugubina zones (see Enclosures 1 to 4).

The second paper of the series by Beiranvand et al. (2013) interpreted genetic stratigraphic sequences and sea-level cycles based on the response of palynomorphs in the complete section of the Gurpi Formation in the Danial Section. The present paper interprets the depositional sequences and sea-level cycles in the Gurpi Anticline, where the type section of the Gurpi Formation is defined (James and Wynd, 1965). It then shows that the nine Gurpi Formation sequences interpreted in the Danial Section can be correlated to the Gurpi Section over a distance of about 70 km (Figure 1).
GEOLOGICAL SETTING

During the late Cretaceous and Paleocene, the northeastern region of the Arabian Plate was covered by the Neo-Tethys Ocean (Ziegler, 2001; Sharland et al., 2001; Motiei, 2003; Alavi, 2004). The region of the present-day Zagros Mountains was a NW-trending foredeep basin situated southeast of the Zagros Suture Zone (Figure 1; Ziegler, 2001; Alavi, 2004). The deepest part of the basin was located next to the suture and a broad shallow-marine shelf extended to the west over most of the Arabian Plate (Koop and Stoneley, 1982). During that time, an upwelling system of currents developed in the southeastern Neo-Tethys Ocean resulting in the deposition of thick organic-rich, relatively deep-marine shales and argillaceous lime mudstones in the Zagros Foredeep (Kolodny, 1980; Parrish and Curtish, 1982; Almogi-Labin et al., 1990, 1993; Eshet et al., 1994; Ziegler, 2001). The Gurpi Formation was deposited during the late Campanian to late Danian in this asymmetric foredeep basin southeast of the Zagros Suture (Bahroudi and Talbot, 2003).

The Gurpi Formation is about 340 m thick in the Gurpi and Danial sections (Figure 1, Enclosures 1 and 2), and consists of dark-gray to gray marly shales, marls and marly limestones. In these sections it overlies the Ilam Formation and the contact is a sharp disconformity surface with no evidence of subaerial erosion or weathering. It is conformably overlain by purple clayey shale and marl layers of the basal part of the Pabdeh Formation. The carbonates of the Emam Hassan Member occur in the middle part of the Gurpi Formation, and extend throughout the Zagros Basin with some distinctive lateral facies variations. In the study area, the member consists of thin-bedded pelagic and hemipelagic marls and argillaceous lime mudstones with planktonic foraminiferal assemblages (Wynd, 1965). This member has a gradational contact with the underlying strata making them practically indistinguishable except for their lithologic color.

STUDY PROGRAM

The study program started in the field by measuring the thickness of the two sections and recording their lithology, sedimentary structures and geometry. Natural gamma-ray (NGR) was...
Table 1
Abbreviations

| Abbreviation | Definition                                                                 |
|--------------|----------------------------------------------------------------------------|
| AOM          | Amorphous organic matter                                                   |
| GR           | Gamma-ray                                                                  |
| HI           | Hydrocarbon index                                                          |
| HST          | Highstand systems tract                                                    |
| IZ           | Interval zone                                                              |
| km           | Kilometer                                                                  |
| K/Pg         | Cretaceous/Paleogene boundary                                              |
| KTB          | Cretaceous/Tertiary boundary                                               |
| Kyr          | Thousand years                                                             |
| LOZ          | Lowest-occurrence zone                                                     |
| LOSZ         | Lowest-occurrence subzone                                                  |
| LST          | Lowstand systems tract                                                     |
| m            | Meter                                                                      |
| Ma           | Million years before present                                               |
| MFS          | Maximum flooding surface                                                   |
| Myr          | Million year                                                               |
| NGR          | Natural gamma-ray                                                          |
| OI           | Oxygen index                                                               |
| PMI          | Palynological marine index                                                 |
| PRSZ         | Partial-range subzone                                                     |
| Rm           | Marine palynomorphs richness                                               |
| RT           | Terrestrial palynomorphs richness                                           |
| SB           | Sequence boundary                                                          |
| S/C          | Spiniferites/cyclonephelium ratio                                          |
| SEM          | Scanning electron microscope                                               |
| T-R          | Transgressive-regressive                                                   |
| Tm           | Maximum temperature                                                        |
| TOC          | Total organic carbon                                                       |
| TRZ          | Taxon-range zone                                                           |
| TS           | Transgressive surface                                                       |
| TST          | Transgressive systems tract                                                |
| XRD          | X-ray diffraction                                                          |
| XRF          | X-ray fluorescence                                                         |
| TRZ          | Taxon-range zone                                                           |
| XRF          | X-ray fluorescence                                                         |
| XRF          | X-ray fluorescence                                                         |
| Al           | Aluminium                                                                   |
| Ba           | Barium                                                                      |
| Ca           | Calcium                                                                     |
| Cs           | Caesium                                                                     |
| Fe           | Iron                                                                        |
| Ir           | Iridium                                                                     |
| K            | Potassium                                                                   |
| Mg           | Magnesium                                                                   |
| Mo           | Molybdenum                                                                  |
| Nb           | Nibumbium                                                                   |
| OI           | Oxygen index                                                                |
| HI           | Hydrocarbon index                                                          |
| OI           | Oxygen index                                                                |
| HI           | Hydrocarbon index                                                          |
| Al           | Aluminium                                                                   |
| Ba           | Barium                                                                      |
| Ca           | Calcium                                                                     |
| Cs           | Caesium                                                                     |
| Fe           | Iron                                                                        |
| Ir           | Iridium                                                                     |
| K            | Potassium                                                                   |
| Mg           | Magnesium                                                                   |
| Mo           | Molybdenum                                                                  |
| Si           | Silicon                                                                     |
| Sn           | Stannum                                                                     |
| Th           | Thorium                                                                     |
| Ti           | Titanium                                                                    |
| U             | Uranium                                                                     |
| Zr           | Zirconium                                                                   |

measured using a SURVEY mode in GR-130 portable gamma in the two sections (677 m thick) with a 0.25 m sampling interval (Enclosures 1 and 2). A total of 299 rock samples were collected from the sections, most of which consist of dark-gray to gray, laminated and slightly bioturbated marly shales, marls, and shaley marls with subordinate marly limestones.

A total of 180 samples were selected for thin-section preparation and 106 samples were processed for planktonic foraminiferal biostratigraphy, following the standard method of Keller et al. (1995). In addition, a total of 210 samples were processed for stratigraphic and organic-matter investigations, following the palynological technique described in Wood et al. (1996). A total of 15 samples were prepared for X-ray diffraction (XRD) analysis and 25 powdered bulk samples underwent standard analytical methods of Espitalie et al. (1986) using Rock-Eval II plus TOC (total organic carbon) module to determine TOC, Tmax (maximum temperature), OI (oxygen index), and HI (hydrocarbon index). The distribution of major and trace elements was determined on 52 samples by XRF (x-ray fluorescence) analysis.

Thin sections were studied by optical microscopy, and the data were processed using the routine grain-size distribution analysis (Flügel, 2004) for petrography and microfacies analysis so as to correlate the facies between the sections. Dating of time lines was established using a detailed planktonic foraminiferal biozonation and dinocyst events in the sections (Enclosures 3 and 4). X-ray techniques (XRD, XRF and SEM) were used as the main methods to identify mineral phases, clay content, chemical composition (major and trace element analysis), and microplanktonic species diversity. Palynofacies analysis, geochemical data (TOC, Tmax, OI, and HI), and natural gamma-ray spectroscopy, which are strongly dependent on variation in depositional environments (Tyson, 1995), were used as multi-disciplinary approaches to interpret sea-level cycles. The interpretation of this data is described in more detail below.

Facies Analysis

Field descriptions of lithology, sedimentary structures, trace fossils and strata surfaces, together with microfacies analysis of the formation, led to the identification of four main sedimentary facies related to sea-level variations.

(I) Gray marls and argillaceous limestones to carbonate mudstone/wackestone containing minor debris of planktonic and rare benthic foraminifera; this facies occurs in shallowing upward parasequences of the lowstand systems tract (LST) of each depositional sequence. It is consolidated following a period of erosion and/or non-deposition after the falling stage of the sea-level cycle.
(2) Dark-gray to gray marls and marly shales to carbonate wackestone, wackestone-packstone and packstone, with abundant planktonic and rare benthic foraminifers; this facies occurs in deepening upward parasequences of the transgressive systems tract (TST) during the rising stage of the sea-level cycle.

(3) Gray fossiliferous marls and shaley marls containing abundant planktonic and rare benthic foraminifera occur in the parasequences of the early highstand systems tract (HST).

(4) Light-gray to cream marls interbedded with marly limestones, characterized by planktonic foraminifera wackestone, containing common trace fossils with abundant oxidized minerals suggest deposition during period of low sea level within outer-neritic to upper-slope settings.

A hardground surface at the top of each depositional sequence marks a major sedimentological change from the gray marly limestones and marls below, to the marls and clayey marls above. The latter contains several resistant layers of cream marly limestones. This pattern suggests a rising sea level, sometimes with fluctuations.

Planktonic Foraminifera

Nutrient supply, oxygen, temperature and salinity are the main environmental parameters that control variations in the relative abundances of planktonic foraminifers’ species (Huber et al., 1999; Gebhardt et al., 2004). It has also been demonstrated that the eustatic sea level can fluctuate with temperature. Therefore, shifts in the percentage and morphotype groups of planktonic foraminifera indicate changing environmental conditions, which can be linked to water depth (e.g. Boersma and Shackleton 1981; van der Zwaan et al., 1990; Huber et al., 1995, 1999; Nederbragt et al., 1998; West et al., 1998; Premoli Silva and Sliter, 1999; Gebhardt et al., 2004). Accordingly, four main planktonic foraminiferal morphogroups are recognized:

(1) Heterohelicids are interpreted as opportunists indicating high productivity or unstable conditions (Nederbragt et al., 1998; West et al., 1998; Premoli Silva and Sliter, 1999), which may point to the deepest habitats (Huber et al., 1995, 1999).

(2) Hedbergellids (non-keeled group) are interpreted as surface dwellers (Huber et al., 1995). These are considered to be open-marine species, which dominate when favorable conditions at greater depths do not exist (shallow-water depths or oxygen minimum zones; Leary et al., 1989; Koutsoukos and Hart, 1990; West et al., 1998; Premoli Silva and Sliter, 1999).

(3) The Whiteinella and Praeglobotruncana group indicate intermediate water-depth habitats (Huber et al., 1995, 1999).

(4) The Rotalipora and Dicarinella (keeled genera) group are interpreted as deep open-marine dwelling species (Huber et al., 1995, 1999; Premoli Silva and Sliter, 1999), and can represent different ecological niches. These are incorporated here for environmental interpretation.

Thus, high percentages of planktonic foraminifera, with frequent keeled specimens, are characteristic of deep water. The percentages within the four main environmental index groups indicate values vary widely between 0% and 61%, with a generally increasing trend according to the environmental habitat of each group during sea-level cycles.

Palynomorphs

The main palynological parameters that can be used to interpret relative sea-level changes include:

(1) amount of terrestrially derived organic matter (Posamentier and Vail, 1988; Roberts and Coleman, 1988; Leithold and Bourgeois, 1989);

(2) marine to terrestrial palynomorph ratio (Gregory and Hart, 1992);

(3) the ratio of recycled palynomorphs (Eshet et al., 1988a, b);

(4) depositional organic facies (Habib and Miller, 1989; Habib et al., 1992; Edet and Nyong, 1993);

(5) dinoflagellate species diversity (Habib and Miller, 1989; Habib et al., 1992; Moshkovitz and Habib, 1993).
In this study, the abundance and diversity of marine palynomorphs, represented by the Palynological Marine Index (PMI), and Spiniferites/Cyclonephelium Ratio (S/C) are used as the main palynological parameters to determine changes in depositional environments and transgressive-regressive sequences (Enclosure 1).

The percentages of five main palynological elements (1) amorphous organic matter (AOM), (2) dinocyst, and (3) foraminiferal test linings (as marine palynomorphs), (4) phytoclast and (5) sporomorphs (as terrestrial components) vary from 0–96%. They show a generally increasing trend for marine elements from the transgressive surface (TS) to the maximum flooding surface (MFS), and a decreasing trend for phytoclast and sporomorphs in each sequence. The calculated percentage of palynomorphs is largely controlled by AOM and phytoclast dilution. Large percentages of AOM in the succession resulted from a combination of good preservation (directly related to dysoxic–anoxic conditions) and low-energy environments.

Low percentages of terrestrial elements (phytoclasts and sporomorphs) are mostly related to deep-marine depositional conditions and long-distance transportation of the particles. A very small ratio of sporomorphs to phytoplankton reflects the proximal–distal trend and indicates deep-marine condition for the succession. Plotting these data on ‘AAP’ ternary diagram of Tyson (1995; Figure 2) shows a concentration in the IX and VIII zones implying deep-water basinal setting and stratified marine shelf deposits. On the other hand, determining species diversity of dinocysts indicated that values vary widely between 1 and 42 with a normal increasing trend during relative sea-level rises. Generally, the abundance and diversity of marine palynomorphs increase during deposition of TSTs and the highest diversity is recorded at the MFSs (Enclosure 1).

The PMI that was proposed by Helenes et al. (1998) to support the interpretation of depositional environments is calculated using the formula:

\[
\text{Palynological Marine Index (PMI in %)} = 100 \times \left( \frac{R_m}{R_t} + 1 \right)
\]

Rm is richness of marine palynomorphs (dinoflagellates cysts, acritarchs and foraminiferal test linings) and Rt is the richness of terrestrial palynomorphs (pollens and spores) counted per sample. In the present study, Rm and Rt were expressed as number of species per sample. High values of PMI are interpreted as indicative of normal marine depositional conditions. When the samples have no marine palynomorphs (Rm = 0), the PMI value is 100. The results of determining PMI from counting 210 samples are shown in Enclosure 1. PMI values range widely between 167 and 1,600 with a generally increasing trend from the transgressive surface to the MFSs (Enclosure 1).

Generally, cyst types with different lengths and complexity of processes can be used in environmental analysis (Williams, 1977). The association with dominant long and complex process chorate cysts (such as Spiniferites, Achomosphaera, Oligosphaeridium, Hystrichosphaeridium, and Hystrichodinium) is considered to indicate open-marine shelf environments (Davey and Rogers, 1975; Wall et al., 1977; Brinkhuis and Zachariasse, 1988; Carvalho et al., 2006), and the association of proximate cysts with short, stout and berbed-process (such as Cyclonephelium, Exochosphaeridium, Cleistosphaeridium, and Micrhystridium) reflects a more coastal to nearshore relatively restricted
environment (Brinkhuis and Zachariasse, 1988; Eshet et al., 1992). Optima of the *Spiniferites* group are in most cases associated with a sea-level high and/or an energy low condition. However, the S/C ratio, as additional evidence of the palynologic response to sea-level change, can be defined and taken to reflect a more detailed, smaller-scale change of depositional environments compared to species diversity alone. In general, the S/C ratio shows an increase in the seaward direction and is a good indicator of environmental change in the offshore direction (Harland, 1973). The calculated ratio for 180 samples show a wide range between 0–10, with a typical increasing trend from the TS to the MFS (Enclosure 1). The subsequent change (increase, and then decrease) of the S/C ratio, corresponding with a similar change of species richness, highlights the T-R depositional sequences.

The results of palynofacies analysis indicate that dinoflagellate abundance and diversity, PMI, S/C ratio, and other sedimentary organic-matter parameters are related to the migration of the various depositional environments in response to sea-level changes. They contribute to the recognition of systems tracts and key horizons such as flooding surfaces and sequence boundaries (SB). Accordingly, each palynological cycle develops during a T-S sequence; it starts with a dramatic increase in PMI index, species diversity and S/C ratio in the TST, and the decrease of these criteria during the HST, thus reflecting a complete cycle of relative sea level.

**Geochemical Analysis, Natural Gamma-ray Log and TOC Content**

Inorganic whole rock geochemical data can be used to define depositional facies, stratigraphic surfaces, cycles and sequences reflecting changes in relative sea level. Nine major elements (Ca, Si, Al, Fe, Mg, K, Ba, Rb, and Ti) and six trace elements (Ir, Mo, Zn, Sn, Cs, and Zr) were determined in this study. Data are reported as weight percent oxides (CaO, SiO$_2$, Al$_2$O$_3$, K$_2$O, MgO, BaO, RbO, and TiO$_2$) of major and trace elements. The CaO compound shows the most abundance in the successions (46.8 wt% on average of all samples) and SiO$_2$ and Al$_2$O$_3$ are the other main components with 23.6 wt% and 11.2 wt%, respectively. Others, Fe$_2$O$_3$, K$_2$O, MgO, BaO, RbO, and TiO$_2$ have positive correlations with Al$_2$O$_3$ content. SiO$_2$ contents in hemipelagic marine sediments consist of both biogenic and detrital silica. The SiO$_2$/Al$_2$O$_3$ ratio has a clear negative correlation with Al$_2$O$_3$ content (Enclosure 1).

The samples with high Si/Al ratios, representing high biogenic silica, correspond to those with high TOC content, thus suggesting that TOC content should mainly be derived from sea-surface production of siliceous phytoplankton dominated by diatoms. In this study multi-element geochemistry has been used as a supplement for stratigraphic studies. The part of chemostratigraphy in Enclosure 1 shows the variations of the principal components versus depth to help discriminate between the different chemical signatures of the nine sequences.

The total of natural gamma-ray (NGR) intensity is a function of the combined contributions of K, U, and Th in sediments, matrix density, and matrix lithology. Clay mineral content is often diluted by other components such as biogenic silica. Because of this dilution, if the NGR signal in the sedimentary sequence is to be used to reconstruct the environmental record, it is important to know which chemical components relate to the NGR signal. Thus, NGR measurements can help determine the mineralogy and abundance of clay and other radioactive minerals including micas and feldspars (Serra, 1985). They can also help characterize deposional environments and diagenetic processes in sediments. The NGR intensity of the succession has been plotted with analyzed chemical results in Enclosure 1. The changes of U/Th ratio within the depositional sequences are indicative of the T-R sequences. Changes with depth occur where the parent rocks and organic carbon affect the radioactive element concentrations in specific layers.

Total organic carbon (TOC) in the sediments may be interpreted as a proxy for organic influx. In general, increase in TOC correlates with increasing water depth, but here the organic carbon and Rock-Eval pyrolysis data (Enclosure 1) indicate that TOC values are generally low in the TST and higher values (generally associated with hardgrounds) occur in the HST. The coincident increase in carbonate and proportion of planktonic foraminifera is related to the planktonic foraminifera (mainly heterohelicids) being the main sources of carbonate in the organic-rich shales and marls (Leine, 1986). The pyrolysis data further suggest that all of the kerogens are thermally immature,
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### Table 2
Correlation of Gurpi and global sequences

| Boundary and Sequence | Type Section (meter) | Danial Section (meter) | Rate meter/kyr | Surface | Age |
|-----------------------|----------------------|------------------------|----------------|---------|-----|
| Top Gurpi             |                      |                        |                | SB Th1  | 59.3|
| Gu9                   | 27                   | 20                     | 1.5            | MFS Sel1| 60.6|
| SB Gu9                |                      |                        |                | SB Sel1 | 61.1|
| Gu8                   | 20                   | 14                     | 1.5            | MFS Da4 | 61.7|
| SB Gu8                |                      |                        |                | SB Da4  | 62.1|
| Gu7                   | 22                   | 18                     | 1.0–2.0        | MFS Da2 | 64.5|
| SB Gu7                |                      |                        |                | SB Da1  | 65.1|
| Gu6                   | 50                   | 33                     | 1.0–8.0        | MFS Ma5 | 66.3|
| SB Gu6                |                      |                        |                | SB Ma5  | 67.7|
| Gu5                   | 58                   | 24                     | 1.0–2.0        | MFS Ma4 | 68.0|
| SB Gu5                |                      |                        |                | SB Ma4  | 69.0|
| Gu4                   | 68                   | 94                     | 8.0–9.5        | MFS Ma2 | 69.7|
| SB Gu4                |                      |                        |                | SB Ma2  | 70.1|
| Gu3                   | 28                   | 28                     | 2.5–3.5        | MFS Ma1 | 70.5|
| SB Gu3                |                      |                        |                | SB Ma1  | 70.8|
| Gu2                   | 33                   | 56                     | 3.0–3.5        | MFS Cam9| 72.1|
| SB Gu2                |                      |                        |                | SB Cam9 | 73.1|
| Gu1                   | 32                   | 40                     | 1.5–2.0        | MFS Cam8| 74.5|
| SB Gu1                |                      |                        |                | SB Cam8 | 75.6|

as indicated by the low to slightly elevated temperature maximum (Tmax) values of 422–457°C and a terrigenous source (Type III). However, these data indicate that total organic carbon (TOC) values are generally very low and rarely exceed 0.5 wt%, with average values about 0.23 wt% (Enclosure 1).

**SEQUENCE STRATIGRAPHY**

Haq et al. (1988), in their “Mesozoic–Cenozoic Cycle Chart”, interpreted Campanian–Maastrichtian UZA-4 and Maastrichtian–Paleocene TA-1 supercycles, and dated them between 80.0 and 58.5 Ma in their time scale. They divided these supercycles into cycles or third-order sequences. On the basis of biostratigraphy the Gurpi Formation correlates to third-order sequences UZA-4.4 (75–71 Ma), UZA-4.5 (71–68 Ma) and TA-1.1 to TA-1.3 (68–60 Ma). The cycles of Haq et al. (1988) were revised by Hardenbol et al. (1998) and compiled and recalibrated in the revised geological time scale GTS 2004 (Gradstein et al., 2004) by Snedden and Liu (2011). In the latter updated chart, the Gurpi Formation is calibrated between 75.6 and 59.3 Ma, and correlates to sequences Campanian Ca8 and Ca9, Maastrichtian Ma1 to Ma5, Danian Da1 to Da4, and Selandian Sel1. The sea-level cycles and coastal onlap curves for these sequences are shown in Enclosure 1.

Beiranvand et al. (2013) interpreted the Gurpi Formation in the Danial Section in terms of nine depositional sequences, denoted Gu1 to Gu9 in ascending order (Enclosure 1). The nine Gurpi sequences are interpreted based on facies associations, palynofacies variations, microplanktonic diversity, and geochemical analysis. In the Danial Section, no evidences of subaerial erosion or unconformities is recognized across the Cretaceous/Paleogene boundary, and in general the outer-shelf and deeper-marine marls contain typical correlative conformities (Enclosure 2). Eustasy is believed to have controlled the sea-level cycles, and the sequences are characterized by sequence boundaries (SB), lowstand, transgressive and highstand systems tracts (LST, TST and HST), and maximum flooding surfaces (MFS). The sequence boundaries are given the same name as the overlying sequence (Table 2).
The ages of the sequences are determined from high-resolution planktonic foraminiferal biostratigraphy (Beiranvand and Ghasemi-Nejad, 2013; Enclosures 3 and 4), and correlated to the global sequences by stratigraphic position (Snedden and Liu, 2011). In Table 2, the correlations are listed together with the ages for SBs and MFSs of Snedden and Liu (2011). The sediment accumulation rate is calculated using the thickness of the sequence and depositional age of the global sequence. Note the K/Pg boundary is calibrated at 65.5 Ma in Snedden and Liu (2011), and 66.0 Ma in GTS 2012. In our study the K/Pg is interpreted at the top of Sequence Gu6.

**Gurpi Sequence Gu1**

**SB Gu1** is taken at the base of the studied sections at the boundary between the Gurpi and Ilam formations. It occurs in the upper part of the *Radotruncana calcarea* TRZ and is correlated to SB UZA-4.4 and correlative SB Cam8, which is a major eustatic sea-level drop in the late Campanian (Haq et al., 1988; Hardenbol et al., 1998). Sequence Gu1 is correlated to Campanian Sequence Cam8 between 75.6–73.1 Ma (Snedden and Liu, 2011).

The **TST Gu1** is characterized by decreasing in relative abundance of phytoclast particles and increased abundance of AOM directly related to dysoxic–anoxic conditions and low-energy environments (Enclosure 1). The increased abundance of heterohelicids and keeled genera planktonic foraminifera is interpreted as an open-marine deep-water habitat. Rock-Eval pyrolysis data indicate that TOC values are generally low and kerogen type is dominantly Types II and III (Enclosure 1). Geochemical analysis indicate that the amount of terrigenous minerals (including K, Al, and related elements) increase progressively during the TST. In addition, the U/Th ratio changes are directly related to the sea-level change. These criteria apparently reflect a rapid marine TST during a sea-level rise in outer-neritic conditions, or hydrodynamically lower-energy settings.

The **MFS of Sequence Gu1** is identified by the maximum abundance of heterohelicids and keeled planktonic foraminifera, optimum species diversity, PMI, AOM, CaO components and highest ratios of S/C and U/Th, and scarcity of phytoclast particles. Additionally, GR and NGR logs show the greatest deflections at the MFS. This late Campanian MFS is positioned near the top of the *Radotruncana calcarea* TRZ, immediately below the base of the *Globotruncanella havanensis* PRZ. The dominance of carbonate in these beds reflects maximum accommodation and highest relative sea level, with minimum siliciclastic sediment influx in an overall shelf depositional setting. The HST exhibits a significant and progressive decrease in planktonic foraminiferal percentages and increase in coarser siliciclastic sediments, indicating an overall decrease in water depth and progradation. Major element compounds, except for SiO₂, show decreasing trends, and the GR and NGR logs deflect to the left. The subsequent decreases of U/Th ratio indicate the regression.

**Campanian Gurpi Sequences Gu2 and Gu3**

Dinocyst-based events and associated species, in correlation with the planktonic foraminiferal biozones, imply a Late Campanian age for the sequences Gu2 and Gu3, which are correlated to sequences Cam9 and possibly Ma1 (Snedden and Liu, 2011). Sequence Gu3 is apparently coincident with the brief Ma1 sea-level cycle (ca. 1 Myr) and may have been deposited during a lowstand near the Campanian/Maastrichtian boundary (e.g. Haq et al., 1988; Barrera et al., 1997; Li et al., 1998).

The **TSTs of both sequences** are characterized by low TOC and increasing PMI and microplanktonic diversity. Their MFSs are characterized by an abrupt change in trend of S/C and U/Th ratios, an increasing AOM, and relative abundance and diversity of planktonic foraminifera and dinocysts (100 dinocyst species belonging to 66 genera). The HSTs are reflected by a marked progressive decrease in planktonic foraminifera and dinocyst diversity and an increase in coarser phytoclasts, which indicate decreasing of water depths during regression and progradation (Enclosure 1). All the evidence indicates outer-neritic, deep-marine conditions for these two sequences.
Maastrichtian Gurpi Sequence Gu4

Sequence Gu4 consists of gray marl and marly limestone of the Emam Hassan Member (Enclosures 1 and 2). A total of 61 dinoflagellate cyst species belonging to 53 genera reveals a moderate diversity in the sequence. Based on the bioevents, it has a Maastrichtian age and is correlated to sequences Ma2 and Ma3 (Snedden and Liu (2011)). It has the highest rate of sedimentation, 8–9.5 cm/Kyr, of all the Gurpi sequences (Table 2). SB Gu4 corresponds to a minimum of the U/Th ratio and occurs in the lower part of the *Gansserina gansseri* IZ. The TST occurs in the same interval zone and the increase in water depth is recognized by the increased clay content in the marls, and the abundance and diversity of the microfossil assemblages (Enclosure 1). The MFS occurs in the middle part of the Emam Hassan Member. In the Gurpi Section the MFS is often only recognized by a change in the relative abundance and diversity of planktonic foraminifera and dinocysts. The early HST is characterized by a sharp decrease in PMI values. Light gray to cream marls with carbonate planktonic foraminifera wackestone contain abundant oxidized minerals, suggesting deposition during low sea level within outer neritic to upper slope. The late HST reflects the shallowest environments and the greatest regression.

Late Maastrichtian Gurpi Sequence Gu5

Sequence Gu5 consists of gray marls and marly shales (Enclosures 1 and 2). Based on the planktonic foraminiferal biozones (CF5 and CF4) and correlatable dinoflagellate cysts bioevents, it is mid-Late Maastrichtian and correlated to Sequence Ma4 (Snedden and Liu, 2011). SB Gu5 is characterized by a minimum of the U/Th ratio, a sharp decrease in palynological content and a hardground. The LST is ca. 3 m thick and likely to be equivalent to the uppermost *Contusotruncana contusa* IZ. The TST is recognized as an increase in water depth characterized by the vertical lithologic changes and the components of the microfossil assemblages; it occurs in the *Pseudotextularia intermedia* PRZ. The MFS corresponds to the base of the *Abathomphalus mayaroensis* TRZ, and is correlated to MFS K180 at 68 Ma (Sharland et al., 2001). The overlying sediments are interpreted as a relatively long-lasting HST with drops in dinoflagellate species diversity and an increase in planktonic foraminifera assemblage diversity. The paleoenvironmental indicators represent open-marine, outer-neritic conditions.

Late Maastrichtian Gurpi Sequence Gu6

Sequence Gu6 is the youngest Cretaceous sequence with the K/Pg boundary defining its upper boundary (Enclosures 1 and 2). It comprises dark gray marly shales, and planktonic foraminiferal biozones and dinoflagellate cysts bioevents indicate a latest Maastrichtian age. Sequence Gu6 is correlated to the late Maastrichtian Sequence Ma5 (Snedden and Liu, 2011). Note that the latter authors calibrated the age of 65.1 Ma for the K/Pg boundary as in GTS 2008; however in GTS 2012 it has an estimated age of 66.0 Ma.

SB Gu6 is characterized by a minimum of the U/Th ratio, and a sharp decrease in palynological content. It occurs at the base of the *Pseudoguembelina hariaensis* PRSZ. The LST is ca. 2 m thick, and probably occurs within the basal *Pseudoguembelina hariaensis* PRSZ. The TST occurs within this PRSZ and is characterized by a slight increase in the values of the PMI reaching the highest PMI and diversities in its upper part. The MFS is recognized by increased planktonic foraminifera and dinocysts of moderate diversity (79 dinocyst species belonging to 71 genera) and abrupt increasing of S/C, U/Th ratios, and amount of AOM. The HST corresponds to the latest Maastrichtian *Pseudoguembelina palpebra* PRSZ and *Plummerita hantkeninoides* TRSZ. It may contain a minor regressive phase (sea-level fall) in its middle part, indicated by the low percentage of planktonic foraminifera and slight increase in phytoclasts. At that time, the water depth reached a level where the oxygen minimum zone almost covered the area and permitted the preservation of organic matter. Other minor sea-level falls thought to have occurred at this time are, however, not evidenced by the presence of corresponding “shallow-water” benthic foraminifera. The paleoenvironmental evidence indicates open-marine outer-neritic conditions.
Unlike the Danial locality, where the section is apparently biostratigraphically continuous across the K-Pg boundary, the very latest Maastrichtian and very earliest Paleocene planktonic foraminiferal biozones (the *P. hantkeninoides*, *G. cretacea*, and *P. eugubina* zones) are apparently absent in the Gurpi (northeast Lali) locality. The time period represented by all these zones is only approximately 750,000 years in total and therefore the absence of any or all of them may be due to insufficiently closely spaced sampling.

**Paleocene Gurpi Sequence Gu7**

Sequence Gu7 is the oldest Paleocene sequence, and is characterized by the highest PMI values, particularly in the lower part, and lowest carbonate content. SB Gu7 is correlated to the K/Pg boundary and SB Da1 (Li et al., 1999; Snedden and Liu, 2011). The LST is ca. 1.5 m thick, and corresponds to the basalmost Paleocene planktonic foraminifera *Parvularugoglobigerina eugubina* TRZ (Pa) and *Guembelitria cretacea* PRZ (P0). These two foraminiferal biozones coincide with the lowest occurrences of *Damassadinium californicum* and *Senonisphaera inornata* dinocyst events that are indices for the K/Pg boundary. In addition to the bioevents, there is a correlation between the species richness, iridium anomaly, TOC, quartz, and calcite components (Enclosure 1) that also represent the K/Pg boundary.

The early Danian TST ends at the MFS, which is marked by an increase in frequency and diversity of planktonic foraminifera and dinocyst species (119 dinoflagellate cyst species belonging to 83 genera), and abrupt increase of PMI and AOM amounts and S/C and U/Th ratios. The HST corresponds to the *Parasubbotina pseudobulloides* PRSZ (P1a), and *Subbotina triloculinoides* LOSZ (P1b). It contains abrupt decrease in the abundance and diversity of biota and periodic increases in phytoclasts, which reflect minor sea-level falls. The highest TOC concentration occurs in this systems tract and is probably due to minor sea-level falls because of the occurrence of type III kerogen in these sediments. These minor falls are, however, not evidenced by the presence of corresponding “shallow-water” benthic foraminifera. The bathymetric investigations indicate a marine, mainly outer-neritic, with occasional transgressions, to upper-bathyal conditions for the sequence.

**Paleocene Gurpi Sequence Gu8 and Gu9**

These two sequences comprise dark gray to reddish gray marly shales. Based on the bioevents they are dated as late Danian and Selandian and correlated to sequences Da4 and Sel1 (Snedden and Liu, 2011). The two sequences are characterized by the highest PMI values, particularly in their lower parts. Their MFSs are marked by an increase in frequency and diversity of planktonic foraminifera and dinocyst species and abrupt increases of the PMI and AOM, and S/C and U/Th ratios. The HSTs show probable minor sea-level falls indicated by the abruptly decreasing abundance and diversity of biota and periodic increases of phytoclasts. The most abundant TOC occurs in Sequence Gu9 and is concentrated in the HST. Bathymetric investigations indicate a marine, mainly outer-neritic, with occasional transgressions to upper-bathyal conditions.

**CONCLUSIONS**

Four main lithofacies, integrated with biofacies response to paleoenvironmental changes, indicate that the Upper Campanian–Paleocene Gurpi Formation consists of at least nine depositional sequences. These were deposited in the Zagros Foredeep in settings that varied between middle-to outer-neritic and particularly upper-bathyal depths and hydrodynamically lower-energy conditions. The Gurpi sequences can be correlated to the global sequences compiled by Snedden and Liu (2011).

The Cretaceous/Paleogene (K/Pg) boundary, traditionally referred to as the Cretaceous/Tertiary boundary (KTB), is recognized as at the boundary between Gurpi sequences Gu6 and Gu7. The lowstand systems tract of basalmost Paleocene Gurpi Sequence Gu7 is characterized by planktonic foraminifera *Parvularugoglobigerina eugubina* TRZ (Pa) and *Guembelitria cretacea* PRZ (P0), the
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lowest occurrence of Damassadinium californicum and Senoniasphaera inornata dinocyst events, and a correlation between the species’ richness, iridium anomaly, TOC, quartz, and calcite components—all representative indices for the K/Pg boundary (Enclosure 1).

Arabian Plate maximum flooding surface Maastrichtian MFS K180 (Sharland et al., 2001) is a distinctive mappable surface with an estimated age of at 68 Ma. It coincides to the base of the Abathomphalus mayaroensis TRZ in Gurpi Sequence Gu6, which is correlated to global Maastrichtian Sequence Ma5 (Snedden and Liu, 2011).

The low TOC content of the Gurpi depositional sequences in the TSTs and higher values in HSTs can be interpreted as due to the floodings of planktonic foraminifera (mainly heterohelicids) as the main sources of carbonate in the organic-rich shales and marls. Furthermore, the pyrolysis-data suggest that all of the kerogens present here are thermally immature, as indicated by the low to slightly elevated temperature maximum (Tmax) values of 422–457°C.

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Enclosure 1: Correlation chart of different data to recognize sea-level changes and identify systems tracts and correspondence to the global sea-level cycles and systems tracts. See table 1 for abbreviations.
Enclosure 2a: Danial Reference Section, Pyun Anticline, Northeast Izeh (Iran)

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Enclosure 2b: Gurpi Type Section, Gurpi Anticline, Northeast Lali (Iran)

GeoArabia
Enclosure 3: Full Planktonic Foraminifera Biozonation, Danial Reference Section
Enclosure 4: Full Planktonic Foraminifera Biozonation, Gurpi Type Section

| Nannofossil Event | Planktonic Foraminifera Biozonation (This Study) |
|-------------------|-----------------------------------------------|
|                   | Sample Number | Formation | Member | Lithology | Texture |
|                   |               | Gurpi     | Emam Hassan | Mudstone | Graded bedding |
|                   |               |           |         |          |         |

| Thickness (m) | 340 | 320 | 300 | 280 | 260 | 240 | 220 | 200 | 180 | 160 | 140 | 120 | 100 | 80 | 60 | 40 | 20 | 0 |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|

GeoArabia
Beiranvand, B., E. Ghasemi-Nejad, M.R. Kamali and A. Ahmadi 2014. Sequence stratigraphy of the Late Cretaceous–Paleocene Gurpi Formation in southwest Iran. GeoArabia, v. 19, no. 2, p. 89-102, 4 enclosures

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