Significance of ichnofossils in high resolution sequence stratigraphy: Upper Maastrichtian, Koypeh-Dagh Basin, NE Iran

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Abstract

This study shows that ichnology can be used to refine sequence stratigraphy as well as to interpret the depositional environment of the Kalat Formation (Upper Maastrichtian) in the Central Koypeh-Dagh Basin (NE Iran), Darch-Gaz section. Field studies and petrography of these deposits led to recognize four lithofacies and nine subfacies that formed in the tidal flat (lithofacies A), lagoon (lithofacies B), shoal (lithofacies C), and open marine (lithofacies D) within a carbonate ramp system. Trace fossils in this succession consist of Psilonichnus quietis, Thalassinoides suevius, Diplocraterion parallelum, Rhizocorallium الجنسي, and Ophiomorpha isp. that are classified in the Psilonichnus ichnofacies and Thalassinoides suevius, Diplocraterion parallelum, Rhizocorallium الجنسي, and Ophiomorpha isp. in the Cruziana ichnofacies. Based on lithofacies and ichnofacies analyses, two depositional sequences (DS1 and DS2) were identified, that are composed of transgressive and highstand systems tracts. The maximum flooding surface (MFS) in DS2 is characterized at the top of the bed containing Rhizocorallium الجنسي, while this surface in DS1 is recognized by Diplocraterion parallelum grading into Ophiomorpha isp. in similar lithofacies. This study is an example where ichnology provides additional support for high-resolution sequence stratigraphy in carbonate deposits. Moreover, our study demonstrates that trace fossils could be useful in identification of the MFS in similar lithofacies elsewhere.

Key Words: Ichnofacies, Maastrichtian, System tract, Kalat Formation, NE Iran

Introduction

The main applications of ichnology in sequence stratigraphic analysis are (1) the enhancement of environmental interpretations; and (2) the identification of key surfaces and erosional discontinuities particularly where there is a significant temporal break between the eroding event and the deposited strata (Savrda, 1991; Pemberton and MacEachern, 1995; Pemberton et al., 2001, 2004; Rodriguez-Tovar et al., 2007). Integration of ichnological analysis with sedimentological data can also be used to determine facies and sequence variations depend upon water depth and energy conditions (Pemberton and MacEachern, 1995). In the eastern Koypeh-Dagh Basin, sequence stratigraphic analysis of the Upper Maastrichtian Kalat Formation was carried out by characterizing the lithofacies (Mahboubi et al., 2006). However, identifying sequence stratigraphic trends within the central part of the basin was more difficult due to poor facies expression and scarcity of well-differentiated key boundary surfaces. Here, we combine ichnological and lithofacies studies (based on field observations and the examination of 100 thin-sections) to infer depositional environments, changing environmental conditions, and sequence development within the Kalat Formation in northeast Iran in the central Koypeh-Dagh Basin in the Darh-Gaz region, southeast of the Greater Caspian Region (Fig. 1).

Geological setting

The Koypeh-Dagh Basin was formed after the Middle Triassic orogeny as a result of the closure of the Hercynian Ocean in northeast Iran (Berberian and King, 1981; Şengor, 1987; Şengör et al., 1988; Ruttner, 1993; Alavi et al., 1997; Golonka, 2004). In this basin, sedimentation was nearly continuous from Jurassic through the Neogene (Afshar-Harb, 1969, 1979, 1994; Kalantary, 1987). Five major transgressive and regressive sequences have been identified in the eastern part of the Koypeh-Dagh Basin (Moussavi-Harami and Brenner, 1992). Shallow marine to shoreline sediments of the Early Maastrichtian Neyzar Formation were deposited during relative sea level fall (Moussavi-Harami & Brenner, 1992), while during the Late Maastrichtian, relative sea level rose again and the Koypeh-Dagh Basin became a region of shallow marine environments (Smith et al., 1994; Mahboubi et al., 2006). At this time, the carbonates of the Kalat Formation were deposited in shoreline to inner ramp settings (Mahboubi et al., 2006). In the Early Paleocene time, the redbed...
sediments of the Pesteligh Formation were deposited during complete regression of the sea from the Kopeh-Dagh Basin towards the northwest (Moussavi-Harami, 1993). In the central part of the basin, the Kalat Formation was deposited in a shallow marine carbonate ramp with diagnostic ichnofossils. This formation conformably overlies calcareous sandstones of the Neyzar Formation, and, following a period of erosion, is unconformably overlain by red conglomerates and sandstones of the Pestehleigh Formation (Fig. 2).

**Lithofacies and trace fossils analyses**
A combination of lithofacies and ichnofacies analyses is useful for interpreting depth and energy condition during deposition of different lithofacies associations (Pemberton & MacEachern, 1995). Detail of facies analysis including lithologic features, sedimentary structures and trace fossil content, led to the identification of four (A-D) lithofacies associations (Table 1, Fig. 3).

**Lithofacies association A**
This lithofacies consists of three subfacies: (A₁) Sandy intraclastic packstone-grainstone (Fig. 4A), (A₂) sandy intraclastic and bioclastic packstone-grainstone (Fig. 4B), and (A₃) Sandy bioclastic packstone-grainstone (Fig. 4C). These lithofacies are composed of fine-grained quartz sand (15-20%; 0.6 mm), bivalve debris (5-10%; 0.4 mm), benthic foraminifera (5-20%; 0.2-0.5 mm), echinoderms (5-15%; 0.3 mm) and intraclasts (5-25%; 0.4 mm). Benthic foraminifera consist of *Siderolites* and *Rotalia*. Intraclasts are composed of bioclasts debris (bivalve dominated) associated with micritic matrix. Calcite cement in different shapes and some mud matrix is present in these lithofacies. Trough-cross beds of medium thickness dominate in this lithofacies and the bioturbation index is low.

*Trace fossils.* *Psilonichnus quietis* occurs most commonly as unlined, vertical, Y-shaped and cylindrical tubes. At the studied location (Fig. 6A), these traces have near-vertical main shaft, swelling and bedding-orientation that document a gravity-equilibration style of behavior, and characteristic features include average tube diameter about 15 mm and maximum burrow length of 60 to 80 mm that present in sandy intraclastic packstone-grainstone lithofacies (A₁). *Psilonichnus quietis* is
Psilonichnus quietis was originally described from shallow marine sediments of the Eocene Joban Coal Field in Japan (Myint, 2001), where this ichnospecies occurs in strata which is gradually shifting from a terrestrial setting to transgressive conditions. Psilonichus can be found in different ichnofacies including: (1) Glossifungites ichnofacies of intertidal to supratidal flats/banks sediments (Gingras et al., 1998, 2002; Nesbitt and Campbell, 2006; Pemberton and Frey, 1985) which is mainly controlled by substrate, (2) Psilonichnus ichnofacies, which characterizes backshore to coastal-dune areas (Nesbitt and Campbell, 2006; Pemberton et al., 1992b), and (3) Skolithos ichnofacies that occurs within sediments of the outer-estuarine and bay-mouth setting (Campbell and Nesbitt, 2000; Nesbitt and Campbell, 2002).

**Interpretation** - The cross-bedded strata, grain supported texture and siliciclastic influx characterize high-energy environments (e.g., Nader et al., 2006; Olivier et al., 2008). Psilonichnus quietis have been found in tidal flat sediments, which consist of shifting substrate to high energy conditions during transgression (Fürsich, 1981; Pemberton and MacEachern, 1995; Myint, 2001; Nesbitt & Campbell, 2006). Presence of Psilonichnus in A1 could be assigned to formation of this subfacies closed to marine condition in contrast to other subfacies in the lithofacies A.

### Table 1: Description of lithofacies and ichnofossils recorded in the sections studied.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Description</th>
<th>Ichnofossil</th>
<th>Interpretation</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Sandy intraclastic packstone-grainstone</td>
<td>Psilonichnus quietis</td>
<td>The cross-bedded strata, grain-supported texture and siliciclastic influx with Psilonichnus characterize high energy tidal flat environment</td>
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<td>Sandy intraclastic bioclastic packstone-grainstone</td>
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<td>Sandy bioclastic packstone-grainstone</td>
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<td>B</td>
<td>Peloidal intraclastic packstone</td>
<td>Thalassinoides suevicus</td>
<td>Peloid and mud-supported fabric with low energy trace fossils determine low energy as Lagoon environment</td>
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<tr>
<td></td>
<td>Peloidal bioclastic foraminiferal packstone-grainstone</td>
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<tr>
<td>C</td>
<td>Sandy peloidal intraclastic grainstone</td>
<td>Diplococeratium paralleleum</td>
<td>Grain-supported texture and subangular quartz grains and inarticulates indicate a high-energy shoal environment</td>
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<tr>
<td></td>
<td>Bioclastic intraclastic grainstone</td>
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<td>Bioclastic grainstone</td>
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<tr>
<td>D</td>
<td>Peloidal red algal packstone</td>
<td>Rhizocorallium jenense, Ophiomorpha isp, Diplococeratium paralleleum</td>
<td>The micritic matrix, red algal and spicules sponge indicate low-energy open shelf</td>
</tr>
</tbody>
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Figure 3: Idealized shallowing-upward sequence with lithofacies properties that show complete lithofacies associations in unique shallowing stage. (Abbreviations: Bival= Bivalve, Bryoz= Bryozoa, Foram= Foraminifera, Ech= Echinoides, Qtz= Quartz, In= Intraclast, Freq= Frequency).

Lithofacies association B

Two subfacies were identified in this association: (B1) Peloidal intraclastic packstone (Fig. 4D) and (B2) Peloidal benthic foraminiferal packstone-grainstone (Fig. 4E). This association consists of peloids (10%; 0.1 mm in diameter), benthic foraminifera (10-20%; 1.5 mm) and intraclasts (5-25%; 0.3 mm) and has a higher matrix/cement ratio than lithofacies A. Orbitoides, Lepidorbitoides, Siderolites, Miliolide and Rotalia are dominant foraminifera in this association. Bioclastic debris (bivalve shell) with micritic matrix is components in intraclasts. Bioturbation index is medium.

Trace fossils.- Two trace fossils were found in lithofacies B. Thalassinoides suevicus occurs as isolated and Y-shaped branching cylindrical burrows (e.g., Pemberton and MacEachern, 1995; Fig. 6B). The average diameter of the tubes is 2 cm and the maximum observed burrow length ranges from 10 to 30 cm. This trace fossil is a typical component of three ichnofacies: the Glossifungites, Teredolites or Cruziana (Pemberton and MacEachern, 1995; and Seilacher, 2007). Ophiomorpha isp. is another traces that consists of irregularly inclined cylindrical burrows with a pellet wall structure (Fig. 6C). The diameter of
the cylindrical tubes is approximately 1 cm and maximum burrowing depth is 10 cm. Both of trace fossils present in peloidal intraclastic packstone (B₁).

Figure 4: Microscopic images from lithofacies (XPL), A) Sandy intraclastic packstone-grainstone; B) Sandy intraclastic bioclastic packstone-grainstone; C) Sandy bioclastic packstone-grainstone; D) Peloidal intraclastic packstone; E) Peloidal bentic foraminifera packstone-grainstone; F) Sandy peloidal intraclastic grainstone (Q- quartz, Br- bryozoans, Pl- plagioclase, In- intraclast, P- peloid, F- foraminifera , RA- red algal, Bi- bivalve, P- peloid).

Interpretation. - Presence of peloids (e.g., Cadjenovic et al., 2008), large benthic foraminifera (e.g., Flügel, 2004) and mud-supported fabric (e.g., Wilson, 1975) indicate deposition within shallow low-energy environmental condition (e.g., lagoon). Thalassinoides (Malpas et al., 2005; Wanke & Wanke, 2007) and Ophiomorpha isp. (Monaco et al., 2007) also can form under low energy environmental conditions, which supports this interpretation. Presence of both trace fossils in B₁ subfacies show that B₁ formed in deeper water with respect to B₂. The presence of both Ophiomorpha and Thalassinoides in lower part and only Ophiomorpha in the middle part within subfacies B₁ (Fig 7), show that the lower part was deposited in deeper condition than middle part of succession.
Lithofacies association C
This lithofacies consists of three subfacies: (C₁) Sandy, peloidal and intraclastic grainstone (Fig. 4F); (C₂) Bioclastic and intraclastic grainstone (Fig. 5A), and (C₃) Bioclastic grainstone (Fig. 5B). Intraclasts (5-15%; 0.4 mm in diameter), peloids (2-10%; 0.1 mm), benthic foraminifera (10-25%; 0.2-1.6 mm), and detrital quartz grains (5-20%; 0.4 mm) are dominant particles. Siderolites are the dominant large benthic foraminifera. Intraclasts contain bioclastic debris in a micritic matrix. The ratio of calcite cement to matrix is relatively high in this lithofacies. Bioturbation index is medium.

Trace fossils. Diplacrerion parallelum is a vertical U-shaped burrow with spreiten (e.g., Pemberton & MacEachern, 1995; Fig. 6D). The size is variable, but the average horizontal distance between the corresponding vertical shafts is 25-35 mm. The burrow diameter is between 2 and 3 mm and the maximum burrow depth is between 40-55 mm. This trace fossil present in subfacies C₂ and C₃.

Figure 5: Microscopic images from lithofacies (XPL), A) Bioclastic intraclastic grainstone (In- intraclast, F- foraminifer); B) Bioclastic grainstone (Bi- bivalve, F- foraminifera, E- echinoderm, RA- red algal); C) Peloidal red algal packstone (RA- red algal, P- peloid, F- foraminifera).

Interpretation. Grain-supported texture (e.g., Masse et al., 2003), subangular quartz grains (e.g., Coffey & Read, 2004) and subangular intraclasts (e.g., Cadjenovic et al., 2008) indicate a high energy environment such as bar which was affected by wave action. Diplacrerion parallelum is characteristic of high-energy unstable environments (Fürsich, 1974; Oloriz & Rodriguez-Tovar, 2000). This trace fossil is interpreted as the dwelling structure of a filter-feeder animal (e.g., Cornish, 1986) and occurs in the Glossifungites, Skolithos and Cruziana ichnofacies (Pemberton et al., 2001; Seilacher, 2007). Presence of this trace fossil in subfacies C₁ and C₂ may show deeper condition for deposition of these subfacies than subfaecies C₃.

Lithofacies D
This lithofacies consists of peloidal red algal packstone (Fig. 5C). Red algal remains (35%; 0.3 mm in diameter), peloids (15%; 0.1 mm) and sponge spicules (2%; 0.2 mm) are dominant particles in this lithofacies. Siderolites, Orbitoides and Rotalia are dominant foraminifera. The micritic matrix cement ratio is high. Bioturbation index is high.
Figure 6: Trace fossils from the study area (arrow shows top of the bed): (A) Psilonichnus quietis (vertical), (B) Thalassinoides suevicus (vertical), (C) Ophiomorpha isp. (oblique), (D) Diplocraterion parallelum (vertical), (E) Rhizocorallium jenense (oblique).

Trace fossils.- Rhizocorallium jenense consists of short straight to slightly sinuous horizontal U-shaped spreiten burrow with distinct scratch mark (Fig. 6E). Tube diameter is 3 mm and the width of the spreiten burrow is 20-25 mm. Maximum observed length of the burrow is 75 mm. Ophiomorpha isp. and Diplocraterion parallelum are also present in this lithofacies.

Interpretation.- The presence of micrite (e.g., Adachi et al., 2004), red algae (Thomas et al., 2008) and sponge spicules (Flügel, 2004) suggest a low energy open marine environment. Also, Rhizocorallium jenense is a characteristic trace fossil of soft substrate Cruziana and firm substrate Glossifungites ichnofacies (Pemberton et al., 1992b). Rhizocorallium could be formed in low-energy regimes (R. irregularae; Fürsich, 1974, 1981) with soft substrate or in high-energy regimes...
(Fürsich, 1981; Worsley & Merk, 2001) with soft or firm substrates. Ophiomorpha isp. is also recorded from low-energy environments (Monaco et al., 2007) and occurrences of Diplocraterion parallelum depend upon numerous factors such as unconsolidated substrate, preservation potential and different energy conditions (Fürsich, 1975). In lower part of the succession, only Rhizocorallium present in lithofacies D and in the upper part, Diplocraterion with Ophiomorpha present and in the uppermost part, Ophiomorpha present in lithofacies D, therefore, the lower part can be deposited in deeper water.

Environmental interpretation

Based on lithofacies analysis, the Kalat Formation in the eastern Kopeh-Dagh Basin was interpreted to be deposited in a shallow marine carbonate ramp (Mahboubi et al., 2006). However, lithofacies in the central part of the basin are different from the eastern parts, where trace fossils and ichnofacies were studied for the first time. Lithofacies A and B were deposited in the shallowest parts of a carbonate ramp (under tidal flat and lagoonal conditions). Lithofacies C is a grain-supported and contains coarse bioclasts that was deposited in high-energy environmental conditions. Lithofacies D with abundant algal particles was deposited in a low-energy open-marine environment.

The four identified lithofacies show a characteristic ichnofaunas that are distributed with respect to depth and energy conditions. Lithofacies A is characterized by Psilonichnus and shifting substrate, that was formed in tidal flats and similar transitional environments, while lithofacies B with Thalassinoides suevicus and Ophiomorpha isp. is indicative of lagoonal and low-energy environments. Lithofacies C consists of Diplocraterion (high energy) that is probably related to shifting sediment type on bar forms, whereas lithofacies D contains Rhizocorallium jenence and near bar forms Ophiomorpha and Diplocraterion. Psilonichnus, reported from marginal marine environment (Psilonichnus ichnofacies, Pemberton et al., 2001). In the studied section, Thalassinoides suevicus (common), Ophiomorpha isp. (abundant), Diplocraterion parallelum (rare) and Rhizocorallium jenense (rare) were probably formed on the inner shelf (e.g., Pemberton et al., 2001) in a shallow Cruziana ichnofacies (e.g., Obon-Ikuehoh et al., 2005).

Ichnological approach and sequence stratigraphic interpretation

The two potential fold applications of ichnology to sequence stratigraphy are ground soft-related ichnofacies and other substrate-controlled ichnofacies (Pemberton & MacEachern, 1995; Catuneanu, 2006). Ground soft-related ichnofacies can be used for interpretation of paleodepositional environments and changes of depth and energy conditions through time. Therefore, regression and transgression of paleo-shorelines can be determined with ichnofossil approach. Other substrate-controlled ichnofacies can be used for the identification of unconformities in the rock record and thus has important application in sequence stratigraphy (Catuneanu, 2006). The ichnological approach was used here to characterize soft ground-related ichnofacies as well as interpretation of system tracts and sequence boundaries similar to what have been used in Triassic successions of southern Spain where ichnological approach used for determining Glossifungites ichnofacies as start of transgressive stage (Rodriguez-Tavor et al., 2007). In the past, sequence stratigraphic analyses of the Upper Maastrichtian successions in the eastern Kopeh-Dagh were mainly done on the basis of sedimentological data, while in this study a combination of sedimentological and ichnological data have been used for sequence stratigraphic analysis in the central parts of the basin. Based on trace fossils, different lithofacies were used to identify the system tracts and maximum flooding surfaces, as they are thought to reflect variations in depth and energy conditions. Two depositional sequences (DS1 and DS2) were identified. Lithofacies A (tidal flat) in lower part of strata is divided into A1 and A2. Lithofacies A1 occurs in the basal Kalat Formation and is represented by sandy limestone without any trace fossils. It follows the high stand system tracts (HST) stage, interpreted as a shelf margin wedge (SMW) (e.g., Robaszkynski et al., 1994; Zaghrami et al., 2008). Continuous with lithofacies A2, it has cross bedding and toward the top consists of the Psilonichnus ichnofacies (transition substrate) that shows further seaward at the base of transgressive system tracts (TST). At this stage, lithofacies A2 changes to lagoonal lithofacies B with Ophiomorpha isp. in proximal and Thalassinoides in distal lagoon facies. This lithofacies also changes gradually to lithofacies C.
(shoal) and D (deep marine), which are characterized by *Diplocraterion parallelum* (high energy) and *Rhizocorallium jenense* (low energy), respectively. Therefore these variations indicate that *Psilonichnus ichnofacies* gradually changed into the *Cruziana ichnofacies*. Lithofacies D with red algal packstone and the associated *Rhizocorallium* is interpreted as deeper facies and its top surface in Ds₁ is interpreted as the maximum flooding surface (e.g., Pemberton and MacEachern, 1995; Zonneveld *et al*., 2001)

The HST consists of two shallowing upward parasequences. The first parasequence is composed of lagoonal lithofacies with *Ophiomorpha* isp., and lithofacies C (shoal) with *Diplocraterion parallelum*. The second parasequence is formed by lithofacies B with *Ophiomorpha* isp. and lithofacies A with *Psilonichnus*. Therefore the changes from the *Cruziana ichnofacies* to the *Psilonichnus ichnofacies* demonstrate shallowing in depth at the end of the HST (e.g., Pemberton *et al*., 1992a; Pemberton & MacEachern, 1995).

In Ds₂, the TST begins with lithofacies D (red algal packstone) and *Diplocraterion* that shows this lithofacies was deposited under near shoal condition in a high energy regime. *Diplocraterion* was gradually replaced by *Ophiomorpha* isp. in lithofacies D. Although *Ophiomorpha* isp. is common in shallow water (Pollard *et al*., 1993), it is also present in deeper facies too (Tchoumatchenko and Uchman, 2001; Uchman, 2007). *Diplocraterion parallelum* also has similar condition, because it could have formed in high energy shoal (Fürsich *et al*., 2006) and deeper facies (Seilacher, 2007). Nonetheless *Diplocraterion* dominated in deeper part rather than *Ophiomorpha* (Seilacher, 2007). Thus, the change in abundance from *Diplocraterion* to *Ophiomorpha* within the deep red algal packstone lithofacies could be interpreted as depth variations during the deposition of lithofacies D. The top surface of *Diplocraterion parallelum* bed is interpreted as the maximum flooding surface (MFS). Five shallowing upward parasequences including lithofacies D, C, and B represent the HST stage. Finally after this period, regression occurred in this area and the red beds of the Pestehleigh Formation were deposited in a fluvial depositional system (Moussavi-Harami, 1993). This fluctuation of sea level in the study area during the Late Maastrichtian time closely correlates with the global sea level curve published by Haq *et al.* (1987) (Fig. 7).

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**Figure 7:** Stratigraphic column and sequence stratigraphy of the Kalat Formation in the central Kopeh- Dagh Basin.
Conclusions
This study shows that the combination of ichnofacies and lithofacies analysis is a useful tool in high-resolution sequence stratigraphy and reconstruction of depositional environments.
Four lithofacies of a ramp-type carbonate platform were identified in the Upper Maastrichtian deposits of the central Kopel-Dagh Basin (NE Iran), including tidal flat (A), lagoon (B), bar (C) and open marine (D) environments, comprising the Psilonichnus and Cruziana ichnofacies. Two depositional sequences (DS$_1$ and DS$_2$) were recognized in this stratigraphic interval. DS$_1$ is composed of shelf margin wedge with no trace fossils, while TST contains various trace fossils and the MFS with pelloidal algal packstone as well as Rhizocorallium jenense. The HST is characterized by shallowing-upward lithofacies with elements of the Cruziana ichnofacies and subordinate of the Psilonichus ichnofacies at the top. The second depositional sequence (DS$_2$) begun with deeper water lithofacies of pelloidal red algal packstone containing Diplocraterion parallelum. The MFS was recognized by the occurrence of a Diplocraterion bed, and an early HST was interpreted by the occurrence of a Ophiomorpha isp. in a similar lithofacies.

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