Supplementary File 3

Sedimentary Descriptions and Interpretations of the Dashtijum Measured Section

All descriptions and interpretations below refer to the Dashtijum measured section. A detailed (1:100 scale) sedimentary log and photographs of the Dashtijum section are presented in Supplementary File 1.

Schuchi-poyon Formation Description

The base of the Schuchi-poyon Formation is defined here as the first sandstone bed that occurs above a ~10 m thick gypsum bed that Vlasov (1964) interpreted to be Albian in age based on regional correlation. The unit consists of ~780 m of siliciclastic strata including lenticular to tabular sandstone bodies alternating with maroon to dark red siltstone. The Schuchi-poyon Formation may be correlative with the local Talhab, Gaxdagan, Tagarin, Karikansau, Tubegatan, Shirabad, Akkapchingay, Babatag, and Derbent Formations within the Tajik Basin (Djalilov, 1971; Burtman, 2000). The Schuchi-poyon Formation is named for a hamlet located north of the Sangoba valley

The lower part of the Schuchi-poyon Formation (55-500 m level) is composed of numerous 0.5-6 m thick, upward fining sandstone intervals interbedded with siltstone. The sandstone bodies are generally medium-grained, contain large scale (typical thickness 0.5-1 m) trough and planar cross-stratification, and have erosional bases. Low-angle (< 5°) cross-stratification is also present in the sandstone units. Mudstone intraclasts and pebbly conglomerate lags are common at the bases of these sandstone bodies (Supp. File 1, photograph

A). Individual beds with cross-stratification are up to ca. 3 m thick. Bioturbation is common, including vertical burrows (Supp. File 1, photograph B). Relatively thin (<0.5 m), medium-to fine-grained tabular sandstone beds with vague horizontal stratification are interbedded with siltstone. Locally, sandstone bodies with large trough cross-strata display inversely graded laminae that are composed of frosted grains (Supp. File 1, photograph C). Djalilov (1971) and Starshinin (1972) both noted a conglomeratic layer (interpreted as Cenomanian in age) in nearby sedimentary sections, which may be correlative with a prominent, ~2 m thick, pebbly conglomerate layer in the Dashtijum section (ca. 380 m level). Clast counts from the Schuchi-poyon Formation show that conglomerates are dominated by siltstone (mainly intraclasts) and sandstone clasts. The first appearance of limestone clasts occurs at the 625 m level in the measured section.

The sandstone/siltstone ratio in the Schuchi-poyon Formation increases sharply above the ca. 500 m level. Sandstone bodies are medium-grained and occur in 1-3 m thick simple or amalgamated units, either isolated or more commonly amalgamated vertically to form laterally extensive packages separated by thin siltstone layers (Supp. File 1, photograph E). Sandstone beds are generally horizontally stratified, but occasionally display large amplitude (≤ 1 m) trough cross-stratification Supp. File 1, photograph D) and penecontemporaneous deformation structures (Supp. File 1, photograph F). Above the ca. 690 m level, the Schuchi-poyon Formation contains numerous thick (≤ 5 m), massive sandstone beds that are pervasively bioturbated and contain carbonate nodules. Carbonate nodules are up to a few 10s of cm in diameter, have convoluted shapes, and rarely occur in well-defined beds or layers (Supp. File 1, photograph G). More commonly, they are concentrated into zones that cross-cut bedding and have reduction halos. The upper Schuchi-poyon Formation, which contains abundant carbonate nodules, may be equivalent with carbonate-bearing strata in nearby sedimentary sections that were interpreted to be Turonian to lower Coniacian in age (Djalilov, 1971; Starshinin, 1972).

Schuchi-poyon Formation interpretation

We interpret the Schuchi-poyon Formation to be fluvial channel and overbank deposits (e.g., Miall, 1996). The trough cross-stratified sandstone bodies below the 500 m level of the section with mudstone intraclasts and basal gravel conglomerate lags are typical of meandering fluvial channel deposits (Smith, 1987). Up to 3 m thick sandstone beds with low-angle cross-stratification are interpreted as accretion sets in a point bar system (Allen, 1964). Internal scour surfaces within sandstone beds indicate periods of channel reoccupation. Thinner tabular sandstone beds with predominantly horizontal laminations that are interbedded with siltstone are interpreted as levee or crevasse splay deposits adjacent to the channel systems (Bristow et al., 1999). Localized beds of massive to trough cross-stratified sandstone containing frosted grains and inversely-graded layers are interpreted to be grain-flow deposits that formed in small eolian dunes (Hunter, 1977) on a fluvial floodplain. The upper part (670-820 m level) of the Schuchi-poyon Formation contains widespread bioturbation and carbonate nodules, which are interpreted to represent paleosol development on a sandy floodplain (Bown and Kraus, 1987). The size, shape, and concentrated nature of the carbonate nodules may be associated with calcareous rhizoconcretions (Klappa, 1980) and the development of Calcisols, which can be distinguished by horizons of carbonate dissolution/leaching and reprecipitation/accumulation (Mack et al., 1993; Quade et al., 1995).

Hasarak-bolo Formation description

The top of the Schuchi-poyon Formation and the base of the Hasarak-bolo Formation (837 m level) is defined here by a topographic break and the abrupt appearance of predominantly fine-grained lithofacies. The Hasarak-bolo Formation may be correlative with the local Sarykamysh, Kattakamysh, Akrabat, Modun, Muzrabat, and Disgiryak Formations in the Tajik Basin (Djalilov, 1971; Burtman, 2000). The Hasarak-bolo Formation is named after a village located south of the Sangoba Valley.

The unit is ~500 m thick and consists of siliciclastic strata including massive, maroon/green (often mottled) siltstone interbedded with widely spaced, thin (≤ 0.5 m) tabular, fine-grained sandstone bodies (Supp. File 1, photograph H). Most sandstone beds have horizontal laminae or exhibit climbing and oscillatory-current ripple cross-stratification (Supp. File 1, photograph K), including wavy and flaser bedding Supp. File 1, photograph L). Trough cross-stratification in sandstone bodies is less common, but where present is medium- to large-scale (≤ 0.5 m). Dewatering structures are locally present (Supp. File 1, photograph M). Bioturbation is common and fossils include bivalves in siltstone lithofacies, *Ophiomorpha* burrows (Supp. File 1, photograph J), *Teichichnus* burrows (Supp. File 1, photograph N), and root traces (Supp. File 1, photograph I). Detrital carbonaceous material (coal) is also observed. Thin evaporitic layers containing bedded gypsum and gypsum nodules were observed at the ~1200 m level, which may correlate with isolated gypsum beds in nearby sedimentary sections interpreted by Starshinin (1972) to mark the base of the Campanian. Large, sandstone-filled desiccation cracks are common in the upper part of the Formation (Supp. File 1, photograph O). The upper ca. 100 m of the Hasarak-bolo Formation displays an up-section increase in sand content. Sandstones in this interval consist of fine-grained, horizontally laminated to rippled sandstones with variable bioturbation that are overlain by thin bodies of fining-upward trough cross-stratified sandstone that are also commonly bioturbated.

Hasarak-bolo Formation interpretation

The Hasarak-bolo Formation contains sedimentological evidence of deposition under tidal influence in a marginal-marine setting, perhaps in an estuarine system (Dalrymple et al., 1992). The fine-grained lithofacies that comprise the majority of the unit are consistent with deposition in a tidal-flat environment (Reineck and Singh, 1980). Desiccation cracks and evaporitic layers suggest episodic subaerial exposure and drying. Root traces, bioturbation, red-green mottling, and carbonaceous debris are consistent with plant colonization on exposed supratidal flats (Reineck and Singh, 1980). Broadly lenticular sandstone bodies with ripple cross-stratification, mud drapes, occasional trough cross-stratification, and erosive bases are interpreted as tidal channels and bars (Reineck and Wunderlich, 1968). *Ophiomorpha* and *Teichichnus* burrows suggest deposition in an intertidal to subtidal estuarine tidal bar system (Pollard et al., 1993; Knaust, 2018). The upper ca. 100 m of the Hasarak-bolo Formation that consists of fine-grained, horizontally laminated sandstone is interpreted as upper flow-regime deposition on sand flats and tidal bars. The overlying trough cross-stratified sandstone intervals are interpreted as a tidal-fluvial channel network (Dalrymple et al., 1990).

Sangoba Formation description

The top of the Hasarak-bolo Formation (1338 m level) is defined by a conspicuous color and lithologic change, from pink sandstone to dark green laminated mudstone of the Sangoba Formation (Supp. File 1, photograph P). The Sangoba Formation may be correlative with the local Bulgarin, Udantau, and Daralitau Formations in the Tajik Basin (Djalilov, 1971; Davidzon et al., 1982) and includes part or all of the Akdjar Formation, which has been correlated throughout Central Asia (Burtman, 2000; Bosboom et al., 2017). The Sangoba Formation is named for the Sangoba stream valley.

The Sangoba Formation is divided into three informal members based on lithofacies. The lower member is ~180 m thick and composed of dark green, organic-rich, laminated to massive silty mudstone interbedded with thin (2-40 cm), occasionally fossiliferous, yellow-green fine- to medium-grained sandstone beds (Supp. File 1, photograph R). Fossiliferous sandstone beds commonly include a fossil shell hash at the base. A few thin (~0.5 m) matrix-supported (green mudstone matrix), sub-rounded pebble conglomerate beds are present (Supp. File 1, photograph Q). Thicker (>1 m) sandstone beds with ripple cross-stratification are present near the top of the lower member, which is transitional with the middle member.

The base of the middle member of the Sangoba Formation (1516 m level) is defined as the base of a prominent, ridge-forming, ~15 m thick sandstone body with low-angle trough cross-stratification. The bed has a bimodal grain size distribution of coarse-grained sandstone intercalated with thin (≤ 0.5 m) conglomeratic layers. The middle member is ~115 m thick and is composed mostly of maroon-brown siltstone and interbedded, pink sandstone intervals (Supp. File 1, photograph S). The member is distinguished by its red-brown color, which contrasts with the lower and upper members of the Sangoba Formation. Siltstone intervals in the middle member are generally massive and locally mottled. Ripple and trough cross-stratification, and horizontal lamination are all common in middle Sangoba sandstone beds. The sandstone/siltstone ratio, sandstone bed thickness, and overall grain-size increase up-section. Massive and horizontally stratified sandstone beds are more common in the lower part of the member and sedimentary features include *Skolithos* ichnofacies (Supp. File 1, photograph T), flute casts (Supp. File 1, photograph U), and carbonaceous debris (coal). Trough cross-stratification is most common in the upper part of the member and sandstone beds often fine upward with a gravel to pebble lag at the base (Supp. File 1, photograph V). Conglomerate in the upper part of the middle member is compositionally immature and contains the first granitic clasts in the Dashtijum section.

The contact between the middle and upper members of the Sangoba Formation (1633 m) is defined by a change from red-brown massive siltstone in the middle member to gray-green laminated mudstone and the appearance of thick (> 1 m) limestone beds. Similar thick limestone beds in nearby sedimentary sections were previously interpreted to mark the start of the Maastrichtian (Djalilov, 1971; Starshinin, 1972). Laminated mudstone and marlstone layers in the lower part of the member contain algal laminae, coal lenses, and isolated vertical burrows (Supp. File 1, photograph W). The limestone beds in the lower part of the member contain concentrated shell beds and locally display convoluted lamination and nodular texture (Supp. File 1, photograph X). The upper part of the upper member is composed chiefly of massive, light green-gray mudstone interbedded with yellow-green, fine-grained sandstone with calcareous cement and carbonate concretions/nodules (Supp. File 1, photograph Y). Sandstone beds are tabular, up to ~2m thick, and rarely amalgamated. Bioturbation is common in both the mudstone and sandstone layers and trace fossils are often enriched in calcite and appear micritic (Supp. File 1, photograph Z). Fossiliferous shell beds, including bivalves and grastropods, are common in the fine-grained sandstone beds (Supp. File 1, photograph AA).

Sangoba Formation interpretation

The Sangoba Formation represents a major transgressive event and may correlate with the second (of five total) marine incursion into the Tajik-Tarim Basin since the Late Mesozoic (Bosboom et al., 2013; 2017). The lower member of the Sangoba Formation is interpreted to have been deposited in a low-gradient, mud-dominated shelf/ramp environment (Varban and Plint, 2008). The scarcity of bioturbation and high inferred organic content could indicate that bottom waters were dysoxic (Sageman et al., 2003). Isolated and thin (<0.5 m) sandstone bodies, locally exhibiting ripple cross-stratification, are interpreted as deposits of episodic storm-generated flows (Snedden et al., 1988). Rippled sandstone beds indicate water depths above storm-weather wave-base. Thicker (>2 m) sandstone bodies that transition from planar laminae at the base to ripple cross-stratification at the top are interpreted as the deposits of combined flows during waning storms (e.g., Duke, 1990). Fossiliferous sandstones that include a basal fossil hash are also interpreted as storm deposits (Myrow and Southard, 1996). The matrix-supported conglomerate beds near the base of the upper member (Supp. File 1, photograph Q) are interpreted as subaqueous debris flows (Lowe, 1979).

The middle member of the Sangoba Formation exhibits a wide range of sedimentary features and is interpreted as an overall progradational shoreface sequence ranging in paleo-water depth from the lower shoreface to a fluvial system at the top of the member. The thick, trough cross-stratified sandstone at the base of the member with a bimodal grain size distribution is consistent with deposition in a wave-dominated shoreface (Clifton and Dingler, 1984; DeCelles, 1987; Hart and Plint, 1995; Hampson and Storms, 2003). *Skolithos* burrows also support a shoreface environment (Ekdale, 1985). The middle part (~1540-1570 m) of the middle member, which is characterized by massive red-brown to mottled siltstone interbedded with fine-grained sandstone that occasionally contains coal clasts, may record deposition in estuarine to tidal environments (Dalrymple et al., 1992). Amalgamated trough cross-stratified sandstone beds with conglomerate lags at the top of the middle member are interpreted as fluvial deposits (Miall, 1996). Poorly-sorted, clast-supported pebble conglomerates with a sandy matrix in the upper part of the member are also interpreted to be fluvial in origin.

The upper member of the Sangoba Formation is interpreted as marginal marine to lagoonal deposits. In the lower part of the member, mudstone with coal debris and algal laminae mixed with laminated limestone beds are consistent with deposition in a lagoonal setting (Kendall, 1968). The laminated limestone beds are interpreted as peritidal or lagoonal carbonate (Wright, 1984). In the upper part of the member, interbedded mudstone and fine-grained sandstone are typical of inner shelf (lower shoreface to offshore) deposition in a marginal marine setting (Swift et al., 1987). Extensive bioturbation, locally fossiliferous fine-grained sandstone beds, the lack of sedimentary structures, and the large amount of fine-grained sediment suggest deposition mainly below fair-weather wave-base (Reading and Collinson, 1996). Convoluted laminae and nodular texture is interpreted to be the result of differential diagenesis (Noble and Howells, 1974; Bathurst, 1987). Fossil assemblages (rudists, ostracods, echinoid remains, and calcareous nannofossils) in sample DSH-16-24 from the upper member of Sangoba Formation suggest a low to moderate energy carbonate ramp environment located above mean storm-weather wave-base.

Bukhara Formation description

The base of the Bukhara Formation (~1860 m level) is defined by the disappearance of fine-grained calcareous sandstone beds and the appearance of thick (>1 m) fossiliferous limestone beds. The Bukhara Formation in the Dashtijum section is ~315 m thick and composed of limestone interbedded with siltstone, mudstone, and gypsum. The Bukhara Formation as defined in the Dashtijum section may include part or all of the Turkestan, Alay, and Suzak Formations (Bosboom et al., 2017). Limestone in the lower part of the unit is fossiliferous and contains layers of glauconitic and oolitic limestone. These lower limestone beds are interbedded with laminated, yellow-green siltstone to mudstone that contain thin (up to a few cm) lenses of coal (Supp. File 1, photograph AB). Some siltstone layers are fossiliferous and include rare shell hash beds. Limestone in the upper part of the unit is less fossiliferous and generally intraclastic (Supp. File 1, photograph AC). Thin conglomerate beds composed of limestone clasts with a carbonate mud matrix are locally present. At the very top of the unit is a clay-rich marlstone. Interbedded with the upper limestone beds are laminated to massive, dark-gray to green siltstone and mudstone. Carbonate concretions and nodules are locally present in siltstone and marl layers. The Bukhara Formation contains a prominent 10-15 m thick layer of gypsum interbedded with thin layers of red siltstone (Supp. File 1, photograph AD). A similar succession of interbedded limestone, siltstone, and gypsum in a nearby sedimentary section was interpreted by Davidzon et al. (1982) as Late Paleocene in age. The top of the Bukhara Formation in the Dashtijum section is covered.

Bukhara Formation interpretation

We interpret the Bukhara Formation to have been deposited in a carbonate lagoon/bay to sabkha environment, equivalent to coastal areas surrounding the modern Persian Gulf (Evans et al., 1969; Purser and Seibold, 1973). The association of carbonate, evaporite, and siltstone is typical of sabkha-type environments (Handford, 1981; Alsharhan and Kendall; 2003). The assemblage of glauconitic limestone and oolitic limestone interbedded with calcareous laminated siltstone containing coal lenses in the lower part of the Bukhara Formation is interpreted as lagoonal deposits. Although glauconite is most commonly associated with mid-shelf to upper slope water depths (Odin and Matter, 1981) it also forms in shallow-water marginal marine environments, including lagoons (Chafetz and Reid, 2000; Banerjee et al., 2012). Pelleted lime mud accumulating today in lagoons around Abu Dhabi (Alsharhan and Kendall, 2003) may be a modern analog for the glauconitic limestone in the lower part of the Bukhara Formation. Oolitic limestone has also been documented in lagoon settings (Bathurst, 1967) and modern ooids in the Persian Gulf sabkha system are common on high-energy shoals, beach barriers, tidal channels, and landward lagoon shorefaces (Kendall and Skipwith, 1969). The laminated siltstone beds with coal lenses in the Dashtijum section are consistent with deposition in a tidal flat setting, similar to the mangrove swamps in protected areas of the Persian Gulf today (Kendall, 1968). Interclastic limestone and limestone breccia layers in the Bukhara Formation are interpreted as carbonate tempestites (Aigner, 1982). Tempestites and intraclastic carbonates can form in a variety of settings, but the interbedded, dark gray laminated mudstone suggests an organic-rich, low-energy, restricted environment, which is consistent with deposition in a lagoon or bay (Kenig et al., 1990). Ostracod assemblages in samples DSH-16-26 and DSH-16-28 from the Bukhara Formation are typical of very proximal marine to transitional conditions with high-salinity fluctuations, which also supports a lagoon to peritidal depositional environment. Calcareous nannofossils (including benthic to planktonic foraminifera) are notably scarce or absent in samples DSH-16-26 and DSH-16-28 and rare rudist fragments could have been transported landward during storm events. Evaporite interbedded with red siltstone is characteristic of coastal sabkhas and reflects deposition in a wadi plain to saline mud flat or salt pan environment (Kinsman, 1969; Handford, 1981; Alsharhan and Kendall; 2003).

Baldshuan Formation description

Abrupt changes in color and lithology mark the basal contact of the Shurysay Member of the Baldshuan Formation. In the Dashtijum section, the base of the Shurysay Member is obscured by landslides on both sides of the valley. From a distance, the Shurysay Member was observed on a ridgeline to consist principally of recessive orange-red siltstone with minor interbedded sandstone and conglomerate. Vlasov et al. (1991) mapped the contact between the Bukhara Formation and the Shurysay Member in the Dashtijum region as a bedding-parallel reverse fault that extends along strike for at least 50 km. However, we did not observe any significant discordance in the orientation of bedding across the contact, or any evidence for faulting, and we interpret the contact as an unconformity. This interpretation is consistent with several previous sedimentological studies in the Tajik Basin that document a regional unconformity that removes a significant part of the Eocene section (Bratash, 1970; Varentsov et al., 1977; Davidzon et al., 1982; Burtman, 2000; Nikolaev, 2002). The estimated thickness of the Shurysay member is ~210 m in the Dashtijum section.

The base of the Kamolin Member of the Baldshuan Formation is locally defined (~2385 m level) as the bottom of a thick (~5 m) coarse-grained sandstone to pebble conglomerate bed with trough cross-stratification (Supp. File 1, photograph AE). The Kamolin Member is distinguished from the Shurysay Member by a greater proportion and thickness of sandstone and conglomerate beds compared to siltstone layers. Fine-grained rocks in the Kamolin Member are chiefly laminated, orange-red siltstone and mudstone. Siltstone layers are generally tabular, but include lenticular bodies that fill scours cut into the underlying strata. Locally, multi-colored laminated siltstone (Supp. File 1, photograph AF), thin (≤ 10 cm) marlstone beds, and carbonate nodules are present. Two sandstone lithofacies are common: 1) medium- to fine-grained, horizontally laminated, lenticular sandstone bodies that interfinger with, or occur as lenses within, thicker conglomerate beds (Supp. File 1, photograph AG); 2) very coarse- to medium-grained, upward fining, trough cross-stratified sandstone bodies with gravel to pebble conglomerate lenses. Thick (up to ~15 m), clast-supported, pebble-cobble conglomerate layers are the most characteristic feature of the Kamolin Member (Supp. File 1, photograph AH). Conglomerate beds are generally well-organized, horizontally stratified, imbricated, and tend to be amalgamated into 20-50 m thick, laterally persistent, cliff-forming units. Granitic clasts are common and metamorphic clasts and recycled conglomerate clasts appear for the first time at this level in the Dashtijum section.

The Childara Member of the Baldshuan Formation is generally finer-grained than the Kamolin member and is composed primarily of stacked, fine- to medium-grained sandstone beds that fine upward to siltstone. The sandstone beds are up to several meters thick and interbedded with red-brown massive siltstone. Carbonate nodules (Supp. File 1, photograph AJ) and evidence for bioturbation, including root traces (Supp. File 1, photograph AK), in sandstone and siltstone beds are pervasive throughout the Childara Member. Occasional conglomeratic lenses within upward fining sandstone beds suggest that the sandstone was originally stratified before bioturbation. Where sandstone bodies have not been disrupted by bioturbation or growth of carbonate nodules, they tend to be horizontally stratified. In several locations, thin (< 15 cm), yellow-white marlstone beds (Supp. File 1, photograph AI) extend laterally for up to a few tens of meters. Conglomerate beds in the Childara Member are generally thin (≤ 2 m), lenticular (with steep margins and sharp, erosive bases), well-organized, clast-supported, massive, and rarely have clasts larger than pebble-size. Conglomerate layers locally display trough cross-stratification, imbrication, and contain lenses of sandstone.

Baldshuan Formation interpretation

Our limited observations of the Shurysay Member of the Baldshaun Formation support the previous interpretation of Klocke et al. (2017) who suggested that deposition occurred in shallow fluvial channels and on floodplains dominated by sheet floods. The Kamolin Member is interpreted to have been deposited in a gravelly braided fluvial system (Miall, 1996). Multi-story conglomerate deposits composed of horizontally laminated, clast-supported conglomerate beds with numerous internal erosional surfaces are typical of gravel sheets and longitudinal bars in a braided river system (Boothroyd and Ashley, 1975; Hein and Walker, 1977). Horizontally laminated sandstone lenses within conglomerate layers indicate deposition in temporarily abandoned channels (Miall, 1977). Individual conglomerate beds up to a few meters thick suggest that deposition occurred in a moderately large river system (Leopold and Maddock, 1953). Laminated siltstone and mudstone are interpreted to be overbank deposits.

In the Childara Member of the Baldshuan Formation, the thick zone (> 300 m) of carbonate nodules, bioturbation, and variegated colors associated with the redistribution of iron and magnesium compounds is indicative of numerous superimposed paleosols (Bown and Kraus, 1987). The carbonate nodules represent calcic paleosols (Mack et al., 1993) and some of the thin, uneven carbonate beds associated with the nodules are interpreted as calcrete (Wright et al., 1988). Paleosol development occurs in both sandstone and siltstone bodies, but was not found in conglomerate layers. The Childara Member is interpreted to have been deposited in a shallow, braided to anastomosing, mixed sandy-gravelly fluvial environment (Rust, 1972; Miall, 1996).

The relatively smaller overall grain size (compared to the underlying Kamolin Member and overlying Chingou Formation) in the Childara Member may indicate deposition in a more distal basin position, reduction in accommodation space, or a less vigorous hydro-climatic regime (Heller and Paola, 1992; Wright and Marriott, 1993). Periodic channel abandonment or ephemeral deposition may have been common because paleosols commonly occur directly on the top of channel deposits, which is common in anastomosing fluvial systems (Smith, 1983; 1986). Siltstone and horizontally laminated fine-grained sandstone bodies are interpreted to have been deposited in a floodplain setting. The thin marlstone layers are interpreted as small ephemeral lacustrine systems that formed within an alluvial plain (Nichols and Hirst, 1998), also common in anastomosing fluvial environments (Smith, 1983; 1986).

Chingou Formation description

The base of the Chingou Formation (~3338 m level) is defined by the appearance of large pebble to cobble conglomerates that form prominent topographic ridges and cliffs. The Chingou Formation is mainly composed of gray, clast-supported, well-rounded conglomerate and interbedded orange-pink massive siltstone to very fine-grained sandstone. The alternating lithologies result in a corrugated relief pattern in outcrop (Supp. File 1, photograph AN). Sandstone layers are generally thin (< 2 m) and trough cross-bedded; however, sandstone is almost completely absent from the middle-upper part of the unit, except for small coarse-grained lenses enclosed by conglomerate. Individual conglomerate bodies are well-organized, laterally extensive (at least several 10's of meters), have sharp, erosive bases (Supp. File 1, photograph AM), and amalgamate into thick (≤ 40 m) tabular packages. Up to cobble-size granitic clasts are conspicuous. Some conglomerate layers show crude horizontal stratification, normal grading, and clast imbrication. Siltstone layers extend laterally for up to a few hundred meters. The total thickness of the Chingou Formation is ~980 m in the Dashtijum section.

Chingou Formation interpretation

The Chingou Formation is interpreted as the deposits of a gravel-bed braided river system (Miall, 1977). Thick, clast-supported conglomerate packages are consistent with stacked and laterally amalgamated channels (Smith, 1990). Horizontal stratification with normal grading is interpreted to be related to migrating longitudinal gravel bars and gravel sheets in a bedload dominated, shallow channel network (Rust, 1972; 1978). Sandstone lenses enclosed by conglomerate are interpreted as bar-top deposits (Bristow, 1993). Massive siltstone layers areinterpreted as floodplain deposits and sharp, erosive contacts between siltstone layers and overlying conglomerate suggests rapid migration or avulsion of channels (Bristow and Best, 1993).

Tavildara Formation description

The Tavildara Formation is transitional with the clonglomeratic upper Chingou Formation, but it can be distinguished by the disappearance of interbedded siltstone layers, an increase in maximum clast size (up to small boulder), and by less well-organized conglomerate lithofacies. Amalgamated conglomerate units in the Tavildara Formation can be over 100 m thick with limited internal erosional surfaces. On the outcrop scale (a few square meters) conglomerate beds are poorly-sorted and crudely horizontally stratified to massive (Supp. File 1, photograph AO). However, organization and normal grading in individual beds (up to >10 m thick) is often apparent from a distance (e.g., face of a cliff; Supp. File 1, photograph AP).

Conglomerate bodies have sharp, erosive bases, commonly with furrows. Clasts are generally sub-rounded and occasionally imbricated. The matrix is composed of medium- to very coarse-grained sandstone. Matrix-supported conglomerate is rare. The dip of bedding decreases from sub-vertical near the base of the unit to ~50°W near the top of the Dashtijum measured section. The measured thickness is ~1600 m; however, the total thickness of the Tavildara Formation in the Dashtijum region is estimated at > 3000 m based on satellite imagery.

Tavildara Formation interpretation

The sedimentology of the Tavildara Formation is consistent with deposition in a proximal braided river system associated with stream-dominated alluvial fans (Rust, 1972; 1978). The depositional setting is interpreted to be similar to the underlying Chingou Formation with laterally and vertically amalgamated gravel-bed channel complexes consisting mainly of gravel-bar deposits. The rarity of internal erosional surfaces within amalgamated conglomerate units suggests high sediment supply (Goff and Ashmore, 1994) and shallow, migrating channels (Hein and Walker, 1977). The large clast size and general absence of floodplain deposits also indicates a high sediment supply and a relatively more proximal setting compared to the underlying Chingou Formation. The Tavildara Formation generally lacks features indicative of deposition in debris-flow dominated alluvial fans, such as matrix-rich and matrix-supported conglomerate (Blair, 1999). Instead, the poorly sorted, clast-supported pebble-boulder conglomerates are consistent with hyperconcentrated flows or clast-rich debris flows (DeCelles et al., 1991). Upward-fining clast size, crude horizontal stratification, and erosive bases to conglomerate bodies are consistent with deposition in channels and longitudinal gravel bars. Average clast size, poor sorting, the absence of fine-grained matrix, and framework support indicates that deposition may have been dominated by high-concentration floods or high-energy streamflow on the surface of an alluvial fan complex (Todd, 1989; Ridgway and DeCelles, 1993).

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Sandstone Petrography Results and Data

Principal grain types identified are monocrystalline quartz (Qm), polycrystalline quartz (Qp), foliated polycrystalline quartz (Qpt), plagioclase feldspar (P), potassium feldspar (K), metamorphic lithic grains (Lm), sedimentary lithic grains (Ls; quartzite, sandstone, and siltstone), and volcanic lithic grains (Lv). Trace minerals were counted, but not included in modal calculations.

Sandstone Petrology Results

Sandstones from the Schuchi-poyon Formation have sublitharenite, feldspathic litharenite, and litharenite compositions, with average Qm/F/Lt = 45/10/45 and Qt/F/L = 70/10/20. The feldspar fraction is roughly evenly divided between K-feldspar and plagioclase. Large percentages of lithic grains are present, including polycrystalline quartz, quartz tectonite, quartzose sandstone/quartzite fragments, volcanic fragments (mainly felsic and vitric grains), chert, shale, and minor phyllite, muscovite, and limestone.

Sandstones from the Hasarak-bolo Formation have feldspathic litharenite to lithic arkose compositions, with average Qm/F/Lt = 44/21/35 and Qt/F/L = 62/20/18. Plagioclase is approximately twice as abundant as K-feldspar in the feldspar fraction. Lithic grains are abundant and include polycrystalline quartz, volcanic fragments (mainly felsic and vitric grains), quartzose sandstone/quartzite fragments, quartz tectonite, chert, and minor shale, limestone, phyllite, and muscovite.

Sandstones from the Sangoba Formation have litharenite compositions, with average Qm/F/Lt = 26/8/66 and Qt/F/L = 54/8/38. Sangoba Formation sandstones contain little to no K-feldspar. Sandstone is rich in lithic grain types, including volcanic fragments (with large percentages of vitric, mafic, felsic, and lathwork varieties), quartzose sandstone/quartzite fragments, polycrystalline quartz, quartz tectonite, limestone, chert, shale, and minor dolostone and phyllite. The fraction of mafic volcanic fragments in sandstones from the Sangoba Formation is notably greater than it is in other sandstones in the Dashtijum measured section.

Sandstones from the Baldshuan Formation have sublitharenite, feldspathic litharenite, and litharenite compositions, with average Qm/F/Lt = 44/8/48 and Qt/F/L = 65/8/27. Plagioclase is 3-5 times more common than K-feldspar. Abundant lithic grains include polycrystalline quartz, volcanic fragments (with large percentages of vitric, mafic, felsic varieties and lesser percentages of lathwork and microlitic varieties), limestone, quartzose sandstone/quartzite fragments, quartz tectonite, schist, phyllite, chert, and minor shale, dolostone, muscovite, and biotite. The appearance of significant fractions of limestone and schistose lithic grains in the Baldshuan Formation (and higher up-section) is conspicuous.

Sandstones from the Chingou and Tavildara Formations have litharenite compositions. Chingou Formation sandstone has average Qm/F/Lt = 52/5/43 and Qt/F/L = 72/4/24. Tavildara Formation sandstone has average Qm/F/Lt = 31/9/60 and Qt/F/L = 53/9/38. Plagioclase is two to three times more abundant than K-feldspar. Lithic grains include polycrystalline quartz, limestone, quartz tectonite, volcanic fragments (with large percentages of vitric, felsic, and microlitic varieties and lesser percentages of mafic and lathwork varieties), quartzose sandstone/quartzite fragments, schist, and minor phyllite, dolostone, chert, and shale.

RAW COUNT DATA

SAMPLE	Formation	Qm	Qp	Qpt	Qss	silt	Q
							TOTAL
DSH_16-1	Schuchi	199	25	12	0	0	236
DSH_16-3	Schuchi	190	46	22	30	36	324
DSH_16-5	Schuchi	120	70	27	111	19	347
DSH_16-7	Schuchi	189	66	18	49	16	338
DSH_16-8	Schuchi	240	16	5	0	3	264
DSH-470	Schuchi	243	58	9	1	17	328
DSH_16-13	Hasarak	185	51	13	22	0	271
DSH_16-14	Hasarak	163	30	6	23	1	223
DSH_16-17	Hasarak	231	36	25	14	15	321
DSH_16-20	Sangoba	108	34	14		46	202
DSH_16-21	Sangoba	71	57	52		79	259
DSH-1430	Sangoba	168	52	22		26	268
DSH_16-30	Baldshuan	224	84	32		52	392
DSH_16-31	Baldshuan	213	32	7		22	274
DSH_16-33	Baldshuan	132	54	11		12	209
DSH_16-33b	Baldshuan	136	42	15		17	210
DSH-2225	Baldshuan	203	58	23	1	31	316
DSH-2566	Baldshuan	215	36	10		35	296
DSH-3174	Chingou	229	51	23		25	328
DSH_16-38	Tavildara	141	59	30	3	17	250

SAMPLE	Formation	K	Kperth	Kmicro	Kmym\rm	P	F
							TOTAL
DSH_16-1	Schuchi	6	0	0	0	74	80
DSH_16-3	Schuchi	2	0	0	0	14	16
DSH_16-5	Schuchi	4	0	0	0	13	17
DSH_16-7	Schuchi	22	0	0	0	3	25
DSH_16-8	Schuchi	39	0	0	0	42	81
DSH-470	Schuchi	2				40	42
DSH_16-13	Hasarak	10				74	84
DSH_16-14	Hasarak	43				83	126
DSH_16-17	Hasarak	25				38	63
DSH_16-20	Sangoba	3				61	64
DSH_16-21	Sangoba	0				20	20
DSH-1430	Sangoba	0				23	23
DSH_16-30	Baldshuan	0				6	6
DSH_16-31	Baldshuan	9				32	41
DSH_16-33	Baldshuan	16				28	44
DSH_16-33b	Baldshuan	8				27	35
DSH-2225	Baldshuan	9				41	50
DSH-2566	Baldshuan	5				31	36
DSH-3174	Chingou	2				18	20
DSH_16-38	Tavildara	11				29	40

SAMPLE	Formation	Phyl	Schist	Serpschist	Marble	Lmet
						TOTAL
DSH_16-1	Schuchi	12	0	0	0	24
DSH_16-3	Schuchi	2	0	0	0	24
DSH_16-5	Schuchi	1	0	0	0	28
DSH_16-7	Schuchi	2	0	0	0	20
DSH_16-8	Schuchi	0	0	0	0	5
DSH-470	Schuchi	1	4			14
DSH_16-13	Hasarak					13
DSH_16-14	Hasarak	2				8
DSH_16-17	Hasarak	1				26
DSH_16-20	Sangoba					14
DSH_16-21	Sangoba	1				53
DSH-1430	Sangoba	0	7			29
DSH_16-30	Baldshuan	8	16			56
DSH_16-31	Baldshuan	1	3			11
DSH_16-33	Baldshuan		7			18
DSH_16-33b	Baldshuan		11		2	28
DSH-2225	Baldshuan	3	7			33
DSH-2566	Baldshuan	3	15			28
DSH-3174	Chingou	3	12			38
DSH_16-38	Tavildara	1	6			37

SAMPLE	Formation	Lv.lath	Lv.microlitic	Lv.felsic	Lv.vitric	Lv.mafic	Lv
							TOTAL
DSH_16-1	Schuchi	13	1	6	33	0	53
DSH_16-3	Schuchi	4	1	17	41	0	63
DSH_16-5	Schuchi	2	2	13	31	0	48
DSH_16-7	Schuchi	6	0	22	35	2	65
DSH_16-8	Schuchi	10	0	49	14	1	74
DSH-470	Schuchi	1	3	38	18	1	61
DSH_16-13	Hasarak	17		28	25	1	71
DSH_16-14	Hasarak	7		39	23		69
DSH_16-17	Hasarak			15	16	5	36
DSH_16-20	Sangoba	28	5	32	51	31	147
DSH_16-21	Sangoba	21	3	17	40	13	94
DSH-1430	Sangoba	15	14	27	20	26	102
DSH_16-30	Baldshuan	3		4	4	4	15
DSH_16-31	Baldshuan	16	1	12	17	7	53
DSH_16-33	Baldshuan	17	6	20	48	10	101
DSH_16-33b	Baldshuan	13	12	32	20	15	92
DSH-2225	Baldshuan	7	4	26	13	5	55
DSH-2566	Baldshuan	3	9	22	17	12	63
DSH-3174	Chingou	3	8	4	11	6	32
DSH_16-38	Tavildara	3	5	14	18	8	48

SAMPLE	Formation	Dolostone	LS	Shale	Chert	Blackchert	Lsed
							TOTAL
DSH_16-1	Schuchi	1	0	22	22	0	45
DSH_16-3	Schuchi	0	4	19	15	0	104
DSH_16-5	Schuchi	0	1	7	11	0	149
DSH_16-7	Schuchi	0	0	4	9	0	78
DSH_16-8	Schuchi	0	5	4	15	0	27
DSH-470	Schuchi		3	1	8		30
DSH_16-13	Hasarak			3	8		33
DSH_16-14	Hasarak		2	7	5		38
DSH_16-17	Hasarak		7	4	8		48
DSH_16-20	Sangoba		19		17		82
DSH_16-21	Sangoba	1	29	18	21		148
DSH-1430	Sangoba	2	39	4	5		76
DSH_16-30	Baldshuan	1	6	1	2		62
DSH_16-31	Baldshuan	5	69	1	3		100
DSH_16-33	Baldshuan	2	75		6		95
DSH_16-33b	Baldshuan	2	71	10	5		105
DSH-2225	Baldshuan	0	4	1	4		41
DSH-2566	Baldshuan		15	10	3		63
DSH-3174	Chingou	4	37	1	4		71
DSH_16-38	Tavildara	7	89	2	5		123

SAMPLE	Ep/Zo	Chlorite	Amph	Musc	Biot	Tourm	ZIRC	ACC
								TOTAL
DSH_16-1	6	2	1	12	0	3	1	25
DSH_16-3	0	0	0	1	0	1	0	2
DSH_16-5				1				1
DSH_16-7				3		1		4
DSH_16-8				2				2
DSH-470				1			1	2
DSH_16-13								0
DSH_16-14		1		6	8			15
DSH_16-17		1		1			3	5
DSH_16-20								0
DSH_16-21				1				1
DSH-1430								0
DSH_16-30								0
DSH_16-31								0
DSH_16-33				1	3	1		5
DSH_16-33b				3	3	2	2	10
DSH-2225				6	3		1	10
DSH-2566		1		5	3			9
DSH-3174				2	3	2	2	9
DSH_16-38						1	1	2

RECALCULATED MODAL DATA

F	Lt	Qm	Sample (strat. Level)	sum	Formation
18.8	34.5	46.7	DSH_16-1 (112)	100	Schuchi
3.6	53.5	42.9	DSH_16-3 (267)	100	Schuchi
3.9	68.3	27.8	DSH_16-5 (390)	100	Schuchi
9.4	36.4	54.2	DSH-470	100	Schuchi
5.6	51.7	42.7	DSH_16-7 (595)	100	Schuchi
18.3	27.5	54.2	DSH_16-8 (725)	100	Schuchi
19.2	38.4	42.4	DSH_16-13 (1122)	100	Hasarak
29	33.4	37.6	DSH_16-14 (1145)	100	Hasarak
14.3	33.2	52.5	DSH_16-17 (1327)	100	Hasarak
5.1	57.6	37.3	DSH-1430	100	Sangoba
14.3	61.7	24	DSH_16-20 (1522)	100	Sangoba
4.5	79.5	16	DSH_16-21 (1615)	100	Sangoba
11.4	42.5	46.1	DSH-2225	100	Baldshuan
8.2	43.1	48.7	DSH-2566	100	Baldshuan
1.35	48.55	50.1	DSH_16-30 (2578)	100	Baldshuan
9.1	43.6	47.3	DSH_16-31 (3080)	100	Baldshuan
4.54	43.54	51.92	DSH-3174	100	Chingou
9.9	60.4	29.7	DSH_16-33 (3235)	100	Baldshuan
8.9	59.6	31.5	DSH_16-38 (4043)	100	Tavildara

F	L	Qt	Sample (strat. Level)	sum	Formation
18.3	22.8	58.9	DSH_16-1 (112)	100	Schuchi
3.4	23.7	72.9	DSH_16-3 (267)	100	Schuchi
3.7	18.3	78	DSH_16-5 (390)	100	Schuchi
9.2	17.3	73.5	DSH-470	100	Schuchi
5.4	19.3	75.3	DSH_16-7 (595)	100	Schuchi
18.1	19.6	62.3	DSH_16-8 (725)	100	Schuchi
18.7	19.3	62	DSH_16-13 (1122)	100	Hasarak
28.64	19.55	51.81	DSH_16-14 (1145)	100	Hasarak
13.55	15.7	70.75	DSH_16-17 (1327)	100	Hasarak
4.9	37.3	57.8	DSH-1430	100	Sangoba
13.8	38.9	47.3	DSH_16-20 (1522)	100	Sangoba
4	39.4	56.6	DSH_16-21 (1615)	100	Sangoba
10.8	20.1	69.1	DSH-2225	100	Baldshuan
8	25.7	66.3	DSH-2566	100	Baldshuan
1.25	16.5	82.25	DSH_16-30 (2578)	100	Baldshuan
9	30.4	60.6	DSH_16-31 (3080)	100	Baldshuan
4.3	24.1	71.6	DSH-3174	100	Chingou
9.65	43.1	47.25	DSH_16-33 (3235)	100	Baldshuan
8.4	38.3	53.3	DSH_16-38 (4043)	100	Tavildara

P	K	Qm	Sample (strat. Level)	sum	Formation
26.5	2.2	71.3	DSH_16-1 (112)	100	Schuchi
6.8	1	92.2	DSH_16-3 (267)	100	Schuchi
9.5	2.9	87.6	DSH_16-5 (390)	100	Schuchi
14	0.7	85.3	DSH-470	100	Schuchi
1.4	10.3	88.3	DSH_16-7 (595)	100	Schuchi
13.1	12.1	74.8	DSH_16-8 (725)	100	Schuchi
27.5	3.7	68.8	DSH_16-13 (1122)	100	Hasarak
28.7	14.9	56.4	DSH_16-14 (1145)	100	Hasarak
12.9	8.5	78.6	DSH_16-17 (1327)	100	Hasarak
12	0	88	DSH-1430	100	Sangoba
35.5	1.7	62.8	DSH_16-20 (1522)	100	Sangoba
22	0	78	DSH_16-21 (1615)	100	Sangoba
16.2	3.6	80.2	DSH-2225	100	Baldshuan
12.4	2	85.6	DSH-2566	100	Baldshuan
3	0	97	DSH_16-30 (2578)	100	Baldshuan
12.6	3.5	83.9	DSH_16-31 (3080)	100	Baldshuan
7.2	0.8	92	DSH-3174	100	Chingou
15.9	9.1	75	DSH_16-33 (3235)	100	Baldshuan
16	6.1	77.9	DSH_16-38 (4043)	100	Tavildara

Lv	Ls	Lm	Sample (strat. Level)	sum	Formation
43.4	36.9	19.7	DSH_16-1 (112)	100	Schuchi
33	54.4	12.6	DSH_16-3 (267)	100	Schuchi
21.35	66.2	12.45	DSH_16-5 (390)	100	Schuchi
58.1	28.6	13.3	DSH-470	100	Schuchi
39.9	47.8	12.3	DSH_16-7 (595)	100	Schuchi
69.8	25.5	4.7	DSH_16-8 (725)	100	Schuchi
60.7	28.2	11.1	DSH_16-13 (1122)	100	Hasarak
60	33	7	DSH_16-14 (1145)	100	Hasarak
32.8	43.6	23.6	DSH_16-17 (1327)	100	Hasarak
49.3	36.7	14	DSH-1430	100	Sangoba
60.5	33.7	5.8	DSH_16-20 (1522)	100	Sangoba
31.9	50.1	18	DSH_16-21 (1615)	100	Sangoba
42.6	31.8	25.6	DSH-2225	100	Baldshuan
40.9	40.9	18.2	DSH-2566	100	Baldshuan
11.3	46.6	42.1	DSH_16-30 (2578)	100	Baldshuan
32.3	61	6.7	DSH_16-31 (3080)	100	Baldshuan
22.7	50.4	26.9	DSH-3174	100	Chingou
40.9	46.7	12.4	DSH_16-33 (3235)	100	Baldshuan
23.1	59.1	17.8	DSH_16-38 (4043)	100	Tavildara