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Mammalian biochronology of the Paleogene-Neogene boundary at Aktau Mountain, eastern Kazakhstan

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With 6 figures and 1 table

Kurzfassung: Am Berg Aktau in der Ili-Depression (östliches Kasachstan) treten Säugetiere der Paläogen-Neogen-Grenze in drei verschiedenen stratigraphischen Niveaus auf. Das unterste Niveau liegt in der unteren Kyzylbulak-Formation; es liefert Brontotheriidae und den Hyracodontiden *Ardynia* und wird vorläufig in das Ergilian (spätes Eozän) gestellt. Der untere Teil der darüber liegenden Aktau-Formation führt Reste des Riesen-Nashorns *Paraceratherium* und wird vorläufig in das Tabenbulukian (spätes Oligozän) gestellt. Im oberen Teil der Aktau-Formation wurde eine Vergesellschaftung mit *Gomphotherium*, *Stephanocemas*, *Brachypotherium* und *Lagomeryx* gefunden. Sie hat eindeutig ein miozänes Alter und stammt vermutlich aus dem späten Untermiozän (spätes Burdigal), entsprechend der europäischen MN 5-Zone und dem späten Shanwangian von China. Die Paläogen-Neogen-Grenze liegt am Berg Aktau also in der Aktau-Formtion.

Abstract: At Aktau Mountain in the Ili depression of eastern Kazakstan, fossil mammals that encompass the Paleogene-Neogene boundary occur at three stratigraphic levels. The lowest level is in the lower Kyzylbulak Formation and produces Brontotheriidae and the hyracodontid *Ardynia* and is tentatively assigned a late Eocene (Ergilian) age. The lower part of the overlying Aktau Formation produces fossils of the giant rhinoceros *Paraceratherium* and is tentatively assigned a late Oligocene (Tabenbulukian) age. The upper part of the Aktau Formation yields a fossil mammal assemblage that includes *Gomphotherium*, *Stephanocemas*, *Brachypotherium* and *Lagomeryx*. It is clearly of Miocene age, probably late early Miocene (late Burdigalian), a correlative of European Reference Level MN 5 and the late Shanwangian of China. The Paleogene-Neogene boundary at Aktau Mountain thus is in the Aktau Formation.

Introduction

The Ili depression of eastern Kazakstan represents the western portion of a paleo-Tien Shan basin that extended into western China. Nonmarine Cenozoic strata deposited in the Ili depression are best exposed at and around Aktau Mountain in the southern foothills of the Dzhungarian Alatau (Fig. 1). The Cenozoic section exposed at Aktau Mountain is about 2.5 km thick and mostly of Neogene and Quaternary age (e.g., LAVROV & RAYUSHKINA 1983). However, the lower third of this section has been assigned by some workers to the Paleogene. Indeed, supposed Shandgolian (early Oligocene) mammals as well as mammals of Miocene age have been reported from the lower part of the Aktau section (e.g., RUSSELL & ZHAI 1987; ABDRAKHMANOVA et al. 1989; TLEUBERDINA et al. 1993). Here, we present a preliminary report on the lithostratigraphy and mammalian biostratigraphy and biochrononology of the Aktau Mountain section to determine the position of the Paleogene-Neogene boundary. All fossils reported here are part of the collection of the Laboratory of Paleozoology, Institute of Zoology, Academy of Sciences of the Republic of Kazakstan (Almaty) and bear KAN catalogue numbers.

Previous studies

This brief review of previous studies of the geology and paleontology at Aktau Mountain is not comprehensive, but instead is aimed at summarizing prior knowledge of the fossil mammals collected there. BAZHANOV & KOSTENKO (1961) reviewed earlier lithostratigraphic studies and the mammalian biostratigraphy at Aktau Mountain. They reported fossil vertebrates collected in 1950 at the lowest mammal-producing horizon as Suiformes, *Ergilia* (= *Ardynia*: RADINSKY 1967) *kazachstanica*, Creodonta, *Clemmys*, Trionychidae and Crocodilia. From a stratigraphically higher level they reported Suiformes, *Prodremotherium*, Indricotheriidae, *Schizotherium*, Rhinocerotidae, *Clemmys* and Trionychidae. BAZHANOV & KOSTENKO (1961) judged the lower horizon to be lower Oligocene and the upper horizon to be upper Oligocene.

RUSSELL & ZHAI (1987: 345-348; also see DMITRIYEVA & NESMEYANOV 1982: 73-78) summarized more recent

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Fig. 1. Map of Kazakstan showing location of Aktau Mountain.

studies and concluded that two fossil mammal levels are present at Aktau Mountain, a lower level with *Ardynia* of Shandgolian (early Oligocene) age and an upper level of late Oligocene (Tabenbulukian) age with *Schizotherium*, *Paraceratherium* and *Prodremotherium*. ABDRAKHMANOVA et al. (1989), BAYSHASHOV (1991) and TLEUBERDINA et al. (1993) subsequently delineated two faunal levels at Aktau Mountain, a lower level with *Paraceratherium* (noted earlier by SAVINOV 1963) that they considered early Miocene (Aquitanian) and an upper level they assigned a middle Miocene (Burdigalian) age that yielded *Gomphotherium*, *Stephanocemas*, *Lagomeryx* and other characteristically Miocene mammals.

Lithostratigraphy

Two lithostratigraphic units of formational rank (i.e., mappable at the 1:25.000 scale) are relevant to the Oligocene-Miocene boundary at Aktau Mountain (ascending order): Kyzylbulak and Aktau Formations (Figs. 2-4).

At the core of the Aktau Mountain anticline (Figs. 2, 3, 4A), the Kyzylbulak Formation is at least 157 m thick (its base is not exposed). About half of the formation is sandstone (32% of the measured section) and conglomeratic sandstone (17%); the other half is mostly mudstone (22%) and shale (15%). Conglomerate is a minor rock type (9%), and one bed of gypsum (4%) is present near the top of the

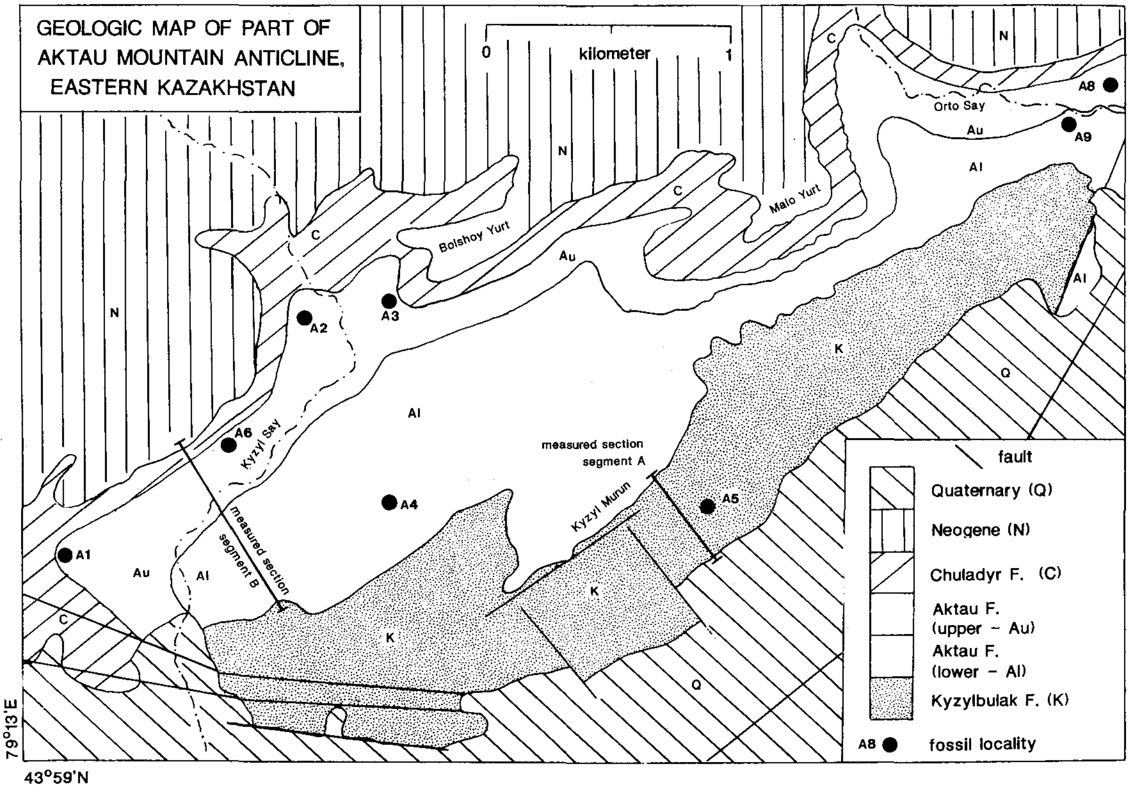

Fig. 2. Geologic map and fossil vertebrate localities at Aktau Mountain anticline.

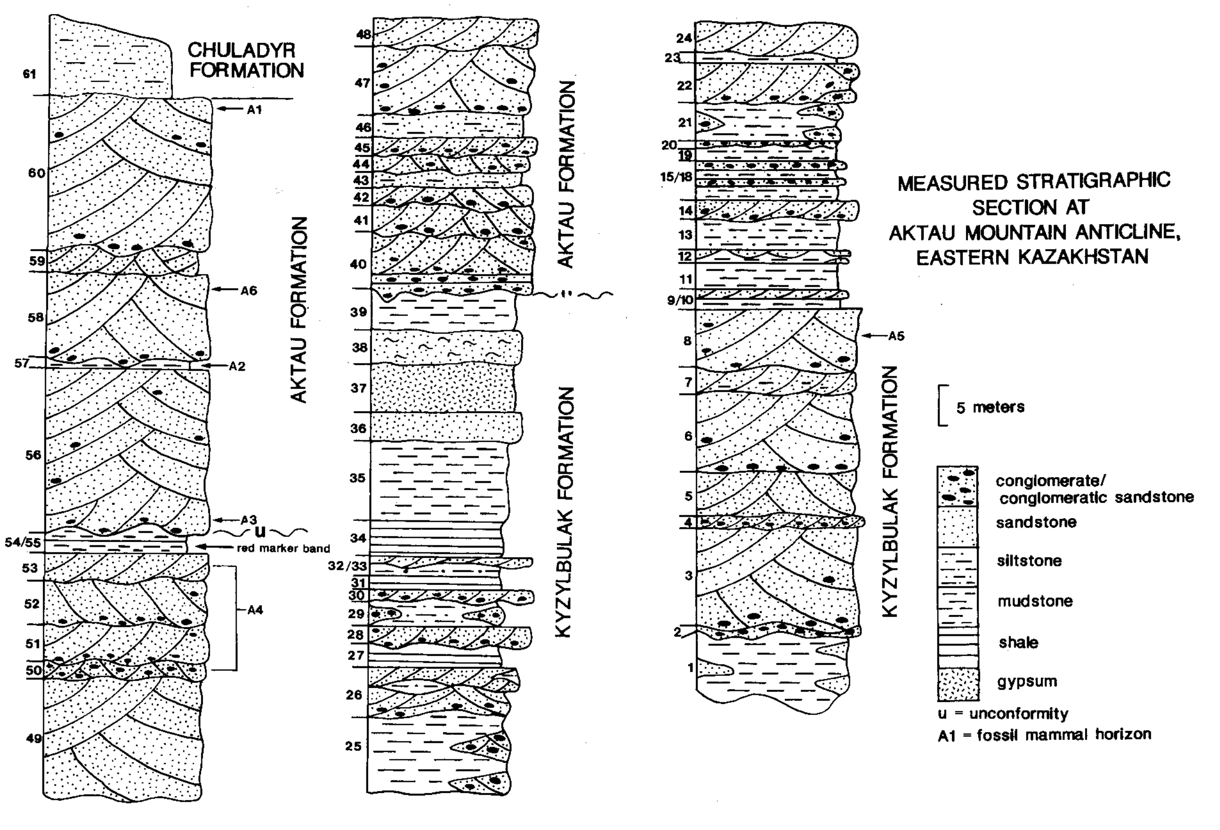

Fig. 3. Measured stratigraphic section of strata that encompass the Paleogene-Neogene boundary at Aktau Mountain. See Appendix for description of numbered lithologic units in measured section.

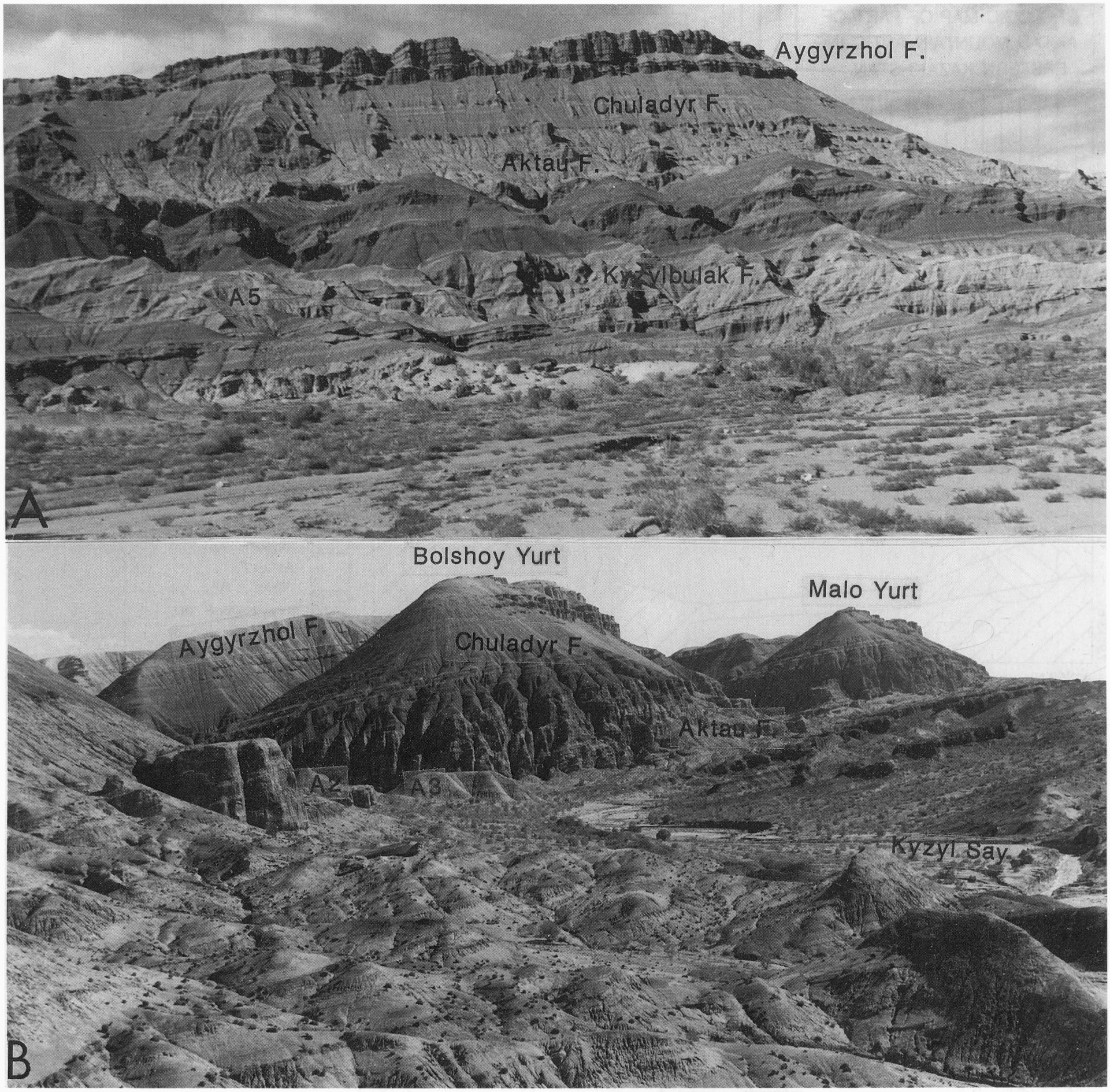

Fig. 4. Photographs of Paleogene-Neogene strata exposed at Aktau Mountain anticline. **A:** Kyzyl Murun looking north. **B:** Kyzyl Say looking east.

formation. The Kyzylbulak Formation is mostly red beds of moderate reddish brown and pinkish gray color, though some beds are shades of gray or dark yellowish orange. Kyzylbulak Formation sandstones are mostly litharenites. Conglomerate clasts are mostly gneissic metamorphic rocks, and a few clasts are rhyolitic volcanic rocks, quartzite and chert. Trough crossbedding is the dominant bedform. There is a lithologic basis for dividing the Kyzylbulak Formation into three members (Fig. 3, units 1-8, 9-37 and 38-39; Fig. 4A), but no such subdivision is attempted here.

The Aktau Formation disconformably overlies the Kyzylbulak Formation at Aktau Mountain (Figs. 3-4). We measured 134 m of Aktau strata that are almost totally conglomeratic sandstone (73% of the section) and sandstone (25%). Only a few thin beds of mudstone and shale (2%) are present. Dominant colors of Aktau Formation sandstone and conglomeratic sandstone are dark yellowish orange, grayish orange and pale yellowish gray. All are trough crossbedded. Most sandstones are hematitic litharenites. Conglomerate clasts are mostly gneissic metamorphics. A laterally extensive, 2-m-thick interval of sandy mudstone near the middle of the Aktau Formation (Fig. 3, units 54-55) is a prominent marker bed. Extensive color mottling and root casts suggest it has undergone pedogenic modification. A 0.9-m-thick bed of gray shale high in the formation (Fig. 3, unit 57) contains fossil leaves (LAVROV & RAYUSHKINA 1983; RAYUSHKINA 1987, 1993). Uppermost sandstones of the Aktau Formation grade upward into muddy, red-bed sandstones of the overlying Chuladyr Formation (Figs. 3-4).

Sedimentation and Vertebrate Taphonomy

We made no systematic effort to study the sedimentation and vertebrate taphonomy of the Kyzylbulak and Aktau Formations. Nevertheless, our stratigraphic and paleontological data allow some tentative conclusions.

We identify two major unconformities in the section we measured (Fig. 3) that define three tectonosequences. A major lithologic change and extensive channeling at the base of the Aktau Formation mark the first unconformity. Underlying strata of the Kyzylbulak Formation are mostly siliciclastic red beds dominated by laterally extensive, texturally and mineralogically immature trough-crossbedded sandstones and conglomeratic sandstones. We interpret these strata (units 1-26) as deposits of a high energy fluvial system of low sinuosity. They grade upward, beginning with unit 27, to lacustrine shales culminated by evaporites (gypsum of unit 37). Units 38-39 may begin another cycle of lacustrine deposition truncated by the basal Aktau Formation unconformity.

Aktau Formation conglomerates and sandstones also represent a high energy, low sinuosity fluvial system. Imbricated pebbles and channel axes suggest paleoflow to the southwest. Presumably the source was a proto-Dzhungarian Alatau to the north-northeast. The lower part of the Aktau Formation (units 40-53) is one tectonosequence capped by an extensive paleosol (units 54-55). A major unconformity at the base of unit 56 underlies upper Aktau deposits very similar to those of the lower part of the formation. Chuladyr Formation red beds – fine sandstones, sandy mudstones and, higher in the section, gypsum – represent lacustrine deposition that culminates this cycle.

In the Kyzylbulak and Aktau Formations, vertebrate fossils occur only in conglomeratic sandstones (Figs. 3-4; Tab. 1). They are exclusively isolated bones, jaw and skull fragments of large mammals (rhinoceroses, brontotheres, ruminant artiodactyls, gomphotheres) and turtle shell fragments and isolated crocodile teeth and scutes. The smallest mammals recovered are mustelid carnivores. No micromammals (insectivores, lagomorphs and rodents) have been found in the Kyzylbulak and Aktau Formations. Vertebrate fossil assemblages in these units clearly are fluvially transported lags of isolated large mammal and reptile bones.

Biostratigraphy and biochronology

Late Eocene (Ergilian)

The stratigraphically lowest mammal-producing horizon at the Aktau anticline is locality A5 in the lower part of the Kyzylbulak Formation (Figs. 2-4A; Tab. 1). Biryukov (1972) assigned KAN 385-1/56, a left calcaneum, astragalus and cuboid (Fig. 5A-I) to the hyracodontid *Ardynia*

Tab. 1. Fossil mammal localities at Aktau Mountain.

locality	UTM	stratigraphic unit	age
A1	44358337E 4872415N	upper Aktau Formation (Fig. 3, unit 60)	Shanwangian
A2*	44359350E 4873266N	upper Aktau Formation (Fig. 3, unit 57)	Shanwangian
A3	44359688E 4873313N	upper Aktau Formation (Fig. 3, unit 56)	Shanwangian
A4	44359662E 4872560N	lower Aktau Formation (Fig. 3, units 50-53)	Tabenbulukian
A5	44360951E 4872569N**	Kyzylbulak Formation (Fig. 3, unit 8)	Ergilian
A6	44358960E 4872900N	upper Aktau Formation (Fig. 3, unit 58)	Shanwangian
A7	44363038E 4874612N	upper Aktau Formation (same leval as A1)	Shanwangian
A8	44362688E 4874171N	lower Aktau Formation (same level as A4)	Tabenbulukian
A9	44362462E 4874058N	lower Aktau Formation (same level as A4)	Tabenbulukian

* fossil plant locality; **horizon extends to 44360540E, 4872206N

(= *Ergilia*: Radinsky 1967) *kazachstanensis* (Gromova 1952). These bones closely resemble the bones of *A. kazachstanensis* described by Gromova (1952), which are, as Radinsky (1967) noted, distinctive among primitive ceratomorphs. However, there is no basis for distinguishing the two species of *Ardynia*, *A. kazachstanensis* and *A. praecox*, on foot bones. Therefore, we identify KAN 385-1/56 as *Ardynia* sp.

From locality A5 we recently collected an incomplete left scaphoid of a brontotheriid (Fig. 5J-K). Maximum antero-posterior length = 68 mm. The bone thus is almost the same size as that of *Rhinotitan mongoliensis* from the Shara Murun Formation of Inner Mongolia, China, illustrated by Wang (1982: pl. 13, figs. 1a-1d). The arcuate magnum facet (not cup-like as in *Brontops*: Osborn 1929: pl. 208) and the saddle-shaped radial facet are other particular points of resemblance, justifying its identification as Brontotheriidae.

Brontotheriids became extinct in Asia at the end of the Ergilian (late Eocene) (Dashzeveg 1993). *Ardynia* is known from both Ergilian and Shandgolian (early Oligocene) horizons in China-Mongolia (Russell & Zhai 1987). Therefore, we regard locality A5 as of possible Ergilian age (Fig. 6), a tentative conclusion that will require additional and more diagnostic mammalian fossils to substantiate.

Late Oligocene (Tabenbulukian)

The lower part of the Aktau Formation (localities A4, A8, A9) has produced only one fossil mammal, the giant indricotheriine hyracodontid rhinoceros *Paraceratherium*.

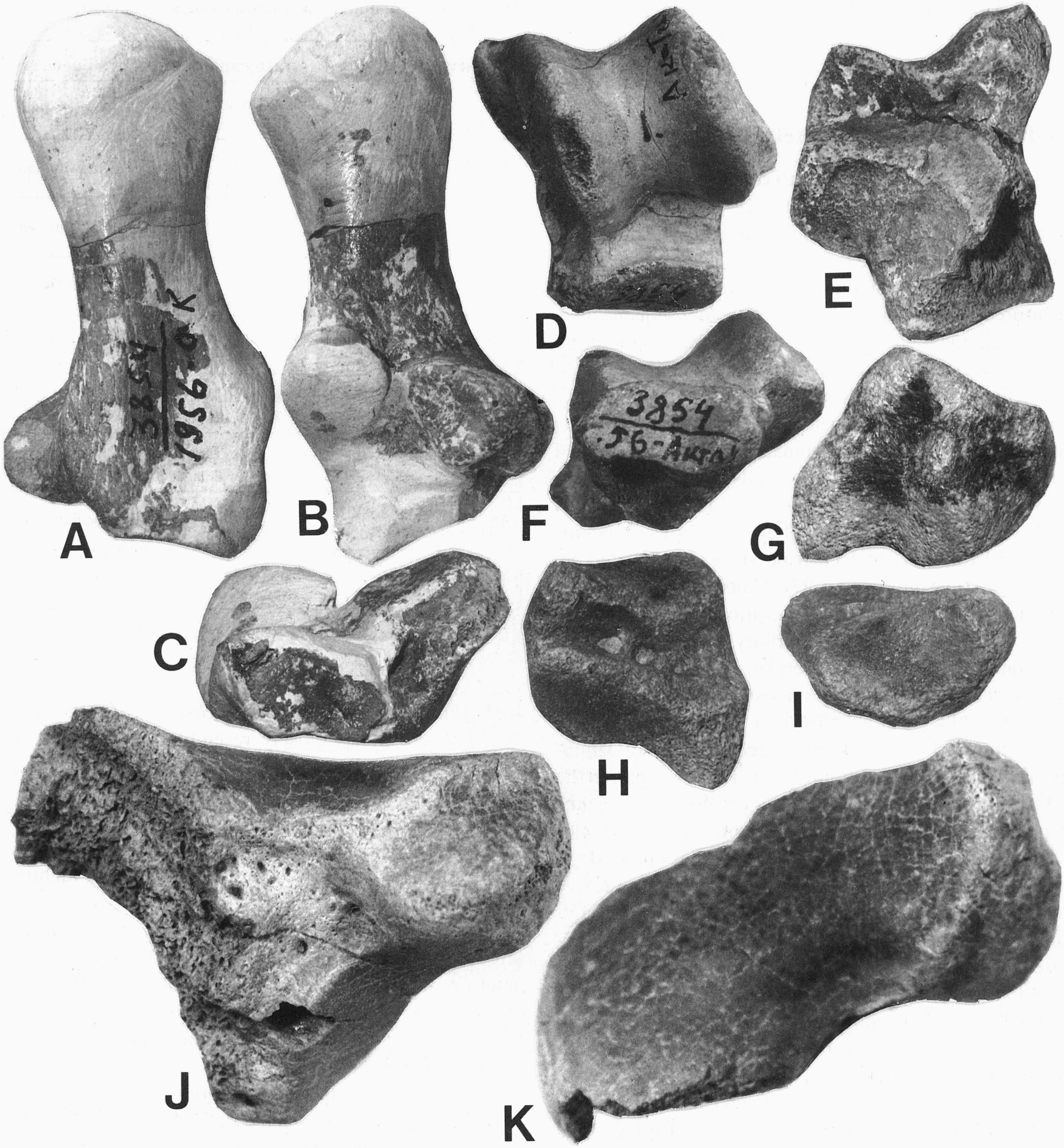

Fig. 5. Perissodactyl postcrania from locality A5 at Aktau Mountain. – **A-I:** KAN 3854-1/56, *Ardynia* sp., left calcaneum, ventral (**A**), dorsal (**B**) and distal (**C**) views; left astragalus, dorsal (**D**), ventral (**E**) and distal (**F**) views; left cuboid, lateral (**G**), medial (**H**) and proximal (**I**) views. **J-K:** KAN 21635, Brontotheriidae, partial left scaphoid, lateral (**J**) and proximal (**K**) views. – All figures ×1.3.

Previous reports of *Paraceratherium* from the Aktau Formation were of fragmentary teeth and postcrania from locality A4, only identifiable as *Paraceratherium* sp. (SAVINOV 1963; ABDRAKHMANOVA et al. 1989) We recently discovered a right dentary with M1-3 at locality A9 most similar to *P. zhajremensis* BAYSHASHOV (in KUDERINA et al. 1988). This specimen will be described in detail elsewhere.

LUCAS & SOBUS (1989) last revised the indricotheres and considered the largest and most derived forms to belong to a single genus *Paraceratherium* (= *Baluchitherium*, = *Indricotherium*, = *Pristinotherium*, = *Dzungariotherium*). The oldest records of *Paraceratherium* are from Nei Monggol, China in strata of Shandgolian age (RUSSELL & ZHAI 1987). The youngest record is of early Miocene age at Bugti, Pakistan (RAZA & MEYER 1984). *Paraceratherium* thus has a temporal range of nearly 10 Ma, from early Oligocene to early Miocene (LUCAS 1994).

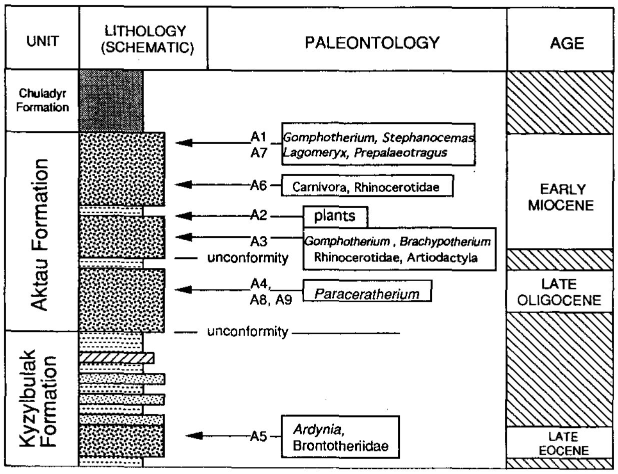

Fig. 6. Summary of lithostratigraphy and mammalian biostratigraphy and biochronology at Aktau Mountain.

Paraceratherium occurrences with reasonably well dated, associated mammal faunas closest to Aktau Mountain are in the Aral Formation along the north shore of the Aral Sea in western Kazakhstan (LOPATIN 1994) and in the Shawa Formation of northwestern Xinjiang, China (QIU & QIU 1995). Based on micromammals, both of these occurrences are no younger than MN1 of the European succession of mammal reference levels, and probably older. MN1 is of latest Oligocene age because the Oligocene-Miocene boundary (= base of Aquitanian) occurs within overlying level MN2 (STEININGER et al. 1991). *P. zhajremensis* was originally described from Atasui in central Kazakhstan where it was collected in association with a paleoflora of probable Oligocene age (KUDERINA et al. 1988). We thus tentatively consider the Aktau Mountain occurrences of *Paraceratherium zhajremensis* to be of late Oligocene (Tabenbulukian) age (Fig. 6), though they could be slightly older.

Early Miocene (Shanwangian)

The upper part of the Aktau Formation has yielded a mammalian fossil assemblage of unquestionable early Miocene age. Documented taxa are *Gomphotherium angustidens*, *Gomphotherium* cf. *angustidens*, *Brachypotherium aurelianse*, *Lagomeryx valessensis*, *Procervulus gracilis*, *Stephanocemas actauensis*, *S. aralensis*, *Prepalaeotragus actauensis* and Caprinae? (ABDRAKHMANOVA et al. 1989; BAYSHASHOV 1991; TLEUBERDINA et al. 1993). *Schizotherium* has been reported from this interval (BAZHANOV & KOSTENKO 1961), and we have collected a single phalanx of a large chalicothere at locality A3, but we cannot confirm the genus-level identification. The stratigraphically lowest gomphothere occurrence is at locality A3, the highest at locality A1.

These mammal occurences bracket a Miocene flora (locality A2) first reported by LAVROV & RAYUSHKINA (1983) and subsequently published by RAYUSHKINA (1987, 1988, 1990, 1993). RAYUSHKINA (1993) listed 56 species from this locality, concluding that xerophytic plants dominate the assemblage. She argued that the Aktau flora is of early Miocene age, older than the Mio-Pliocene 'Paleoturkestan flora' described by KORNILOVA (1966) from the northern Tien Shan to the south of Aktau Mountain.

In the European succession of MN reference levels (DE BRUIJN et al. 1992), *Gomphotherium* and *Brachypotherium* occur in levels MN 4-8, *Stephanocemas* in MN 5-8, *Procervulus* in MN 3-5 and *Lagomeryx* in MN 3-7. This suggests correlation of the upper Aktau Formation assemblage with level MN 5 of the European succession, an age of latest early Miocene (late Burdigalian) on the marine chronostratigraphic scale (STEININGER et al. 1991).

If this correlation is accepted, according to the Neogene mammalian zonation of China published by QIU & QIU (1995), the upper Aktau fauna should be late Shanwangian, even though it only shares two genera (*Gomphotherium* and *Lagomeryx*) with the Chinese Shanwangian. This suggests that the Aktau fauna has closer biogeographic affinities with the European fauna than with the Chinese mammal faunas further east.

Conclusions

Recent collecting and stratigraphic organization of fossil mammal localities at Aktau Mountain in eastern Kazakhstan indicate that three, biochronologically-distinct, fossil-mammal-bearing horizons are present (Fig. 6). The lowest horizon is in the lower Kyzylbulak Formation and is of probable late Eocene (Ergilian) age. The middle horizon, in the lower Aktau Formation, is of Oligocene age, probably late Oligocene (Tabenbulukian). The upper horizon is in the upper Aktau Formation and is of early Miocene (late Burdigalian, Shanwangian) age. The Paleogene-Neogene boundary at Aktau Mountain is within the Aktau Formation.

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Appendix – Measured Stratigraphic Section Across the Paleogene-Neogene Boundary at Aktau Mountain, Eastern Kazakhstan (Fig. 3)

Segment B – Measured on the NW flank of Aktau anticline from the gully SE of Kyzyl Say to the cliff NW of the Say. Strata dip 8° to N50°W. Section starts at UTM 44359110E, 4872225N and top is at UTM 44358910E, 4872986N.

Chuladyr Formation:

61. Muddy sandstone; light brown (5 YR 5/6) and yellowish gray (5 Y 8/1); medium grained; subangular; litharenite; calcareous; massive; slope former. not measured.

Aktau Formation:

60. Sandstone; dark yellowish orange (10 YR 6/6); medium to very coarse grained; subrounded; litharenite; slightly calcareous; contains lenses of pale greenish yellow (10 Y 8/2) and dark yellowish orange (10 YR 6/6) clay-ball conglomerate and conglomerate lenses with the same clast lithology as unit 56; trough crossbedded; locality A1 in top 2 m of unit. 21.7 m.
59. Sandstone; yellowish gray (5 Y 7/2) with pale yellowish

orange (10 YR 8/6) mottling; very fine to medium grained; subangular; micaceous litharenite; locally hematitic; trough crossbedded; forms a prominent gray band and shoulders on hill slope. 3.6 m.

58. Sandstone and conglomeratic sandstone; same colors and lithology as unit 56; locality A6 is 18 m above base of unit. 12.3 m.

57. Shale; olive gray (5 Y 4/1) and light olive gray (5 Y 6/1); not calcareous; caps gray benches on western side of Kyzyl Say; this unit is lenticular because it is locally chopped out by basal scour of unit 58; locality A2. 0.9 m.

56. Sandstone and conglomeratic sandstone; dark yellowish orange (10 YR 6/6); very fine to coarse grained; subrounded; very hematitic litharenite; trough crossbedded; unit is mostly sandstone with trough bases of hematitic concretions and metamorphic rock breccia every 2 to 3 m; locality A3 in lower 5 m. 23.2 m

55. Sandy mudstone; mottled pale red (10 R 6/2) and pale olive (10 Y 6/2); not calcareous; pedoturbated; units 54 and 55 form a prominent, laterally extensive red marker band. 0.6 m.

54. Sandy mudstone; pale reddish brown (10 R 5/4) with flecks of yellowish gray (5 Y 8/1); not calcareous. 1.4 m.

53. Sandstone; dark yellowish orange (10 YR 6/6); very fine to medium grained; subrounded; hematitic quartzarenite; calcareous; trough crossbedded. 3.4 m.

52. Sandstone with lenses of conglomerate; dark yellowish orange (10 YR 6/6); coarse to very coarse grained; subrounded; hematitic litharenite; conglomerate clasts are grayish orange (10 YR 7/4), dark yellowish orange (10 YR 6/6) and olive gray (5 Y 3/2) quartzite and limestone; calcareous; trough crossbedded. 6.1 m.

51. Conglomeratic sandstone; same colors and lithology as unit 40; approximate top of unit is cut by NW bank of Kyzyl Say. 5.5 m.

50. Conglomeratic sandstone; dark yellowish brown (10 YR 4/2) and dark yellowish orange (10 YR 6/6); medium to very coarse grained; subrounded; hematitic litharenite; conglomerate clasts are hematitic concretions that are light brownish gray (5 YR 4/1) and dark yellowish orange (10 YR 6/6); trough crossbedded; some conglomeratic lenses weather to indurated ledges; on the SE flank of Kyzyl Say this unit caps the dip slope; locality A4 in units 50-53. 2.0 m.

49. Sandstone with lenses of conglomeratic sandstone; same colors and lithology as unit 47. 17.1 m.

48. Sandstone with lenses of conglomeratic sandstone; same colors and lithology as unit 41. 4.1 m.

47. Sandstone and conglomeratic sandstone; same colors and lithology as interbeds of units 40 and 41; deeply weathered. 9.4 m.

46. Sandstone; same colors and lithology as unit 43 with some interbedded lenses of unit 41 lithology; forms a prominent pink marker band locally. 3.1 m.

45. Conglomerate; same colors and lithology as unit 40. 2.3 m.

44. Conglomerate; same colors and lithology as unit 42. 2.0 m.

43. Sandstone; light brown (5 YR 5/6) and grayish orange (10 YR 7/4); very fine grained; subangular; hematitic litharenite; micaceous; not calcareous; bioturbated to massive; forms a prominent pink band locally. 1.9 m.

42. Conglomerate; same colors and lithology as unit 40 except clasts are smaller; trough crossbedded. 2.0 m.

41. Sandstone; yellowish gray (5 Y 8/1) with some dark yellowish orange (10 YR 6/6) mottling; fine to medium grained; subrounded; micaceous quartzarenite; not calcareous; some thin lenses of conglomerate of unit 40 lithology at trough bottoms; trough crossbedded. 3.3 m.

40. Conglomerate and conglomeratic sandstone; sandstone matrix is dark yellowish orange (10 YR 6/6), fine to very coarse grained, subrounded litharenite; conglomerate is matrix supported with clasts of gneissic metamorphic rocks up to 15 cm in diameter that are mostly medium dark gray (N4), light brownish gray (5 YR 6/1), and very light gray (N8); calcareous; lower 1-2 m are laminated in fining upward cycles; overlying strata are trough crossbedded; unit grades upward to unit 41 as sandstone becomes dominant over conglomerate; clasts are imbricated to the S/SW. 8.2 m.

unconformity

Segment A – Measured up the south-facing slope of Kyzyl Murun, beginning at the anticlinal nucleus (yadro). Section starts at UTM 44360735E, 4872276N and ends at UTM 44360880E, 4872735N. Section dips 8° to N40°W.

Kyzylbulak Formation:

39. Mudstone; moderate brown (5 YR 4/4); not calcareous; forms a dark red slope. 5.5 m.

38. Sandstone; light brown (5 YR 5/6); medium grained; subrounded; hematitic quartzarenite; calcareous; heterolithic with numerous mud flasers; ripple laminated in small scale trough sets. 4.6 m.

37. Gypsum with clayey matrix; gypsum is white (N9); clayey matrix is same colors and lithology as unit 36; locally this unit lenses into the base of unit 38; caps a cliff. 6.1 m.

36. Sandstone with sandy shale interbeds; moderate reddish orange (10 R 6/6); fine to coarse grained; subrounded; clayey quartzarenite; sandy shale is moderate red (5 R5/4) and light greenish gray (5 G 8/1), very calcareous; unit is blocky and massive and forms base of cliff capped by unit 37. 3.6 m.

35. Shale; moderate reddish brown (10 R 4/6) with yellowish gray (5 Y 8/1) mottles; very calcareous; forms a prominent slope below the cliff formed by units 36-37. 10.9 m.

34. Sandy shale; same colors and lithology as unit 27. 5.2 m

33. Conglomeratic sandstone; same colors and lithology as unit 14. 0.4 m.

32. Sandy mudstone; same colors and lithology as unit 13. 1.5 m.

31. Sandstone; same colors and lithology as unit 27; contains sheets of selenite. 1.6 m.

30. Conglomeratic sandstone; same colors and lithology as unit 14. 1.4 m.

29. Sandy mudstone; same colors and lithology as unit 13. 3.4 m.

28. Conglomeratic sandstone; same colors and lithology as unit 14. 2.7 m.

27. Shale and sandstone; shale is same colors and lithology as unit 26; sandstone is light greenish gray (5 G 8/1), very fine grained, subrounded quartzarenite; not calcareous. 3.0 m.

26. Sandstone and shale; sandstone is grayish yellow (5 Y 8/4), very fine to fine grained, subrounded, calcareous, hematitic subarkose; shale is banded pale olive (10 Y 6/

2) and pale red (5 R 6/2) with dark yellowish orange (10 YR 6/6) mottling, sandy and not calcareous. 2.7 m.

25. Conglomerate interbedded with sandy mudstone; conglomerate is same colors and lithology as unit 22; sandy mudstone is same colors and lithology as unit 13. 14.3 m.

24. Sandstone; pinkish gray (5 YR 8/1); very fine grained; subrounded; subarkosic; calcareous; trough crossbedded; some lenses of sandy mudstone of unit 13 lithology. 4.3 m.

23. Sandy mudstone; same colors and lithology as unit 13. 0.9 m.

22. Conglomeratic sandstone; matrix is pinkish gray (5 YR 8/1), very fine to coarse grained, subangular calcareous subarkose; clasts are moderate reddish orange (10 R 6/6), pale olive (10 Y 6/2) and brownish gray (5 YR 4/1) cherts, volcanics and gneissic metamorphic rocks up to 10 cm in diameter; some lenses of sandy mudstone of unit 13 lithology; clasts are imbricated to the south; trough crossbedded. 5.3 m.

21. Sandy mudstone; same colors and lithology as unit 13; has some 1-m-thick lenses of conglomeratic sandstone of unit 14 lithology. 5.7 m.

20. Conglomeratic sandstone; same colors and lithology as unit 14. 0.2 m.

19. Sandy mudstone; same colors and lithology as unit 13. 2.4 m.

18. Conglomeratic sandstone; same colors and lithology as unit 14. 0.7 m.

17. Sandy mudstone; same colors and lithology as unit 13. 1.4 m.

16. Conglomeratic sandstone; same colors and lithology as unit 14. 0.7 m.

15. Sandy mudstone; same colors and lithology as unit 13. 1.7 m.

14. Conglomeratic sandstone; moderate reddish brown (10 R 4/6); very fine to coarse grained; subrounded; litharenite; not calcareous; subangular clasts up to 3 cm in diameter are mostly novaculitic cherts, rhyolitic volcanics and gneisses; matrix supported; trough crossbedded; forms a ledge. 2.7 m.

13. Sandy mudstone; moderate reddish brown (10 R 4/6) with calcareous concretions that are light greenish gray (5 GY 8/1); forms a slope. 4.4 m.

12. Sandstone and sandy shale; sandstone is light gray (N7) and dark yellowish orange (10 YR 6/6), very fine to medium grained, lithic quartzarenite; sandy shale is same color and lithology as unit 9; sandstone crops out as three, hummocky to trough crossbedded ledges intercalated with the shale. 1.8 m.

11. Sandy shale; same color and lithology as unit 9. 3.8 m.

10. Sandstone; light gray (N7) with moderate reddish orange (10 R 6/6) staining; very fine to coarse grained; subangular; lithic quartzarenite; calcareous; heterolithic trough crossbedding, with flasers of sandy shale of unit 9 lithology; some hummocky beds. 0.4 m.

9. Sandy shale; moderate reddish brown (10 R 4/6); calcareous; slope former 1.0 m.

8. Sandstone and conglomeratic sandstone; dark yellowish orange (10 YR 6/6); fine to very coarse grained; subangular; micaceous; hematitic quartzarenite; conglomerate clasts resemble those of unit 3 but are less quartzite dominated; trough crossbedded; locality A5 is 8-9 m above base of unit. 9.3 m.

7. Sandstone; same color and lithology as unit 5. 2.5 m.

6. Sandstone and conglomeratic sandstone; same colors and lithology as unit 3. 10.9 m.

5. Sandstone; dark yellowish orange (10 YR 6/6) with grayish brown (5 YR 3/2) mottling; very fine to medium grained; subangular; not calcareous; trough crossbedded. 6.2 m.

4. Sandstone and conglomeratic sandstone; medium dark gray (N4) to medium gray (N5), weathers white (N9) and dark yellowish orange (10 YR 6/6); very fine to coarse grained; subrounded; micaceous litharenite; calcareous; trough crossbedded; forms a well indurated ledge. 1.2 m.

3. Sandstone and conglomeratic sandstone; medium dark gray (N4), dark yellowish orange (10 YR 6/6), very pale orange (10 YR 8/2) and grayish orange (10 YR 7/4); fine to coarse grained; conglomerate is mostly white quartzite pebbles up to 2 cm in diameter and some gray limestone and other lithics; matrix supported with weak imbrication; trough crossbedded. 13.7 m.

2. Sandstone and conglomeratic sandstone; moderate orange pink (5 YR 8/4) and light brown (5 YR 6/4) with some pale brown (5 YR 5/4) and dark yellowish orange (10 YR 6/6) mottling; fine to coarse grained; subangular; micaceous litharenite; calcareous; trough crossbedded; forms a low bench. 0.2 m.

1. Sandy mudstone and sandstone; mudstone is moderate reddish orange (10 R 6/6) with pale greenish yellow (10 Y 8./2) mottles and not calcareous; thin (up to 8 cm thick) intercalated beds of sandstone are light brown (5 YR 6/4) with medium dark gray mottles, very fine grained, subangular micaceous litharenite; this is the lowest unit to crop out at the core of the anticline 8.4 m

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