Salt structures and hydrocarbons in the Pricaspian basin

Yuri Volozh, Christopher Talbot, and Alik Ismail-Zadeh

ABSTRACT

Pricaspian basin geology is reviewed in the light of 500,000 km of seismic profiles and several thousand wells. We focus on how hydrocarbons from three sources accumulated in relation to the 1800 salt structures in a basin that changed little in planform from the Devonian to the Paleogene. Riphean to Carboniferous shelf sedimentary strata are still flat lying between a poorly known crystalline basement and a base of salt now 10 km deep. Slow and almost continuous sedimentation in the basin center downbuilt huge massifs in Permian salt initially 4.5 km thick. Basin sediments are flat lying or backtilted between down-to-basin growth faults along northern and western margins starved of sediments. By contrast, progradation of Permian sediments from the Urals, Triassic sediments from the South Emba shear zone, and Jurassic sediments from the Dombass-Tuarkyr fold belt downbuilt successive waves of salt structures basinward from margins in the east, southeast, and then the south. A zone of salt overhangs records extrusion that starved basin-marginal salt structures, particularly during a basinwide hiatus in the Early Jurassic. Salt diapirs along polygonal normal faults rooting to the crests of still-potent salt structures through Cretaceous–Paleogene strata indicate that salt upbuilt back to the surface and resumed downbuilding. Coarse clastic fans infill deep canyons incised across the basin by rivers draining to the Caspian in Pliocene times.

INTRODUCTION

Western literature commonly uses the adjectives ''Pre-Caspian'' (earlier than Caspian) or ''Peri-Caspian'' (peripheral to Caspian) to refer to the basin that is approximately 600 km across from west to east and is underlain by Kungurian salt at the northern end of the Caspian Sea (see Figure 1). To avoid such ambiguities in time or space, we use here the Russian ''Pricaspian'' which implies an area

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adjoining the Caspian. To Russian geologists, the Pricaspian depression is a geologic basin defined by the presence of deformed Kungurian salt. As a result, the northwest and southeast borders are traditionally drawn along the margin of the Late Carboniferous–Early Permian platform.

The first oil from the Pricaspian basin came from a well that was drilled 80 m deep above a subsurface salt structure near Karachungur in 1899 (Figure 1). Nobel Brothers and Company in 1911 developed the first oil field there (Dneprov, 1959; Charygin et al., 1964). By the revolution in 1917, oil was being produced from the Dossor and Northern Makat fields (2–3, Figure 1) at South Emba (Dolitsky et al., 1964). One of the first post-revolutionary government directives signed by V. Lenin was to increase production from the South Emba fields to compensate for the isolation of the Baku (Azerbaijan) fields by civil war. Consequently, more than 10 oil fields had been discovered in South Emba prior to World War II. The light crude produced from these fields could be used unrefined to fuel diesel-engine Russian armored vehicles during that war. Between 1960 and 1975, 150,000 km of 2-D seismic profiles and 300 wells identified 1200 salt structures in the Pricaspian basin (Volozh et al., 1989, 1997a). Oil was found in structural traps in faulted Jurassic to Cretaceous strata above salt structures in 65 of the 300 wells. These pools ranged in size from 6 to 30 million bbl, but only the four largest were developed (Votsalevsky et al., 1993).

Up to about 1970, 90% of exploration was focused on oil plays in the postsalt sediments above salt structures, and only 10% sought oil beneath salt. However, by then, only four fields in South Emba still had reserves of more than 6 million bbl and two schools of thought had developed concerning future exploration in the basin; one advocated exploration in subsalt plays, and the other plays above salt structures. Discussions of this kind were forgotten by the end of the 1970s after three supergiant fields, Tengiz (3 billion bbl of oil), Astrakhan (60 tcf of gas), and Karachaganak (46 tcf of gas) were found in subsalt Devonian carbonate reefs at depths of more than 4 km (Votsalevsky et al., 1993; Belopolsky and Talwani, 2000; fields located in Figure 1). No discoveries of comparable size have followed, although 90% of exploration activity since 1970 has been focused on subsalt plays and only 10% focused on the postsalt section.

The subsalt oil in carbonate reservoirs is high in sulfur (>30% S). Only about 36 million bbl of oil per yr can currently be processed safely from the Tengiz field, although reports in the Kazakh press by the government (1999) indicate plans to increase production to 200 million bbl per yr. Production of high-sulfur oil from the deep subsalt fields is five times greater than that of sweet oil from fields in terrigenous sediments above the salt structures. This is despite exploration in the postsalt section since 1970 having led to the discovery of 10 middle-size fields (30–90 million bbl) and one large field having 180 million bbl of oil (Votsalevsky et al., 1993).

The "current" estimate for oil reserves in the Pricaspian basin is about 3.6 billion bbl (data from the Russian Ministry of Geology dated 1998–1999), but this volume is still based on both 1960s data

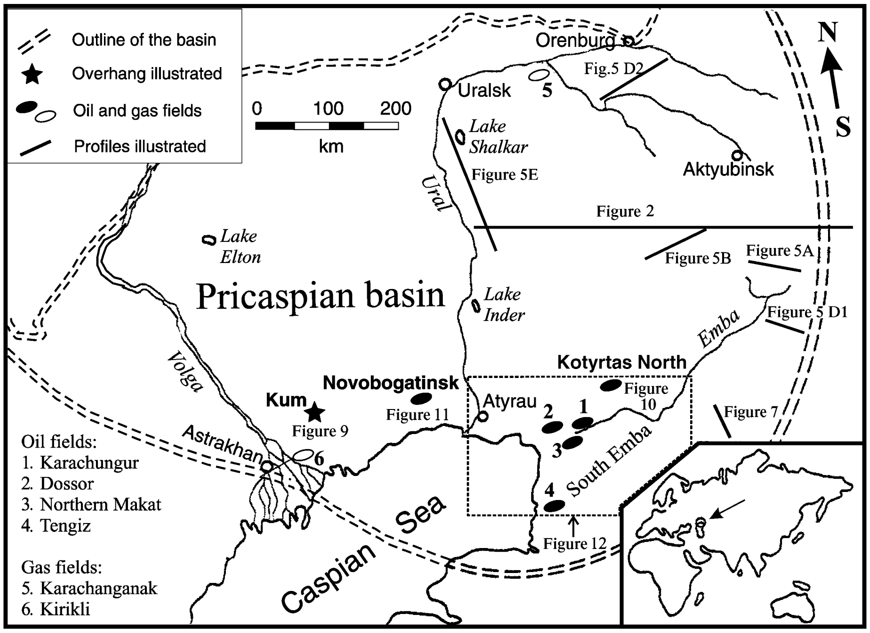


Figure 1. Location map of the Pricaspian basin indicating locations of illustrated seismic and geologic sections, salt overhangs, and oil and gas fields.

and geologic concepts. New data have been collected, and our understanding of hydrocarbon generation, migration, trapping mechanisms, and salt structure evolution have all improved considerably. Consequently, this work is based on interpretations of new data consisting of several thousand wells and approximately 500,000 km of 2-D common depth-point seismic profiles that have been acquired by several geophysical organizations since 1970 under the supervision of both the Russian and Kazakh Ministries of Geology.

This paper outlines the geologic history of the Pricaspian basin, which retained much the same shape from the end of the Sakmarian age (~275 Ma) until the Paleogene (~60 Ma). Deformation of a thick sequence of Permian salt dominated the history of the basin, and two main phases of salt deformation can be distinguished in the Permian–Triassic and Jurassic–Neogene, separated by about 35 m.y. of quiescence from Late Triassic to Middle Jurassic. In the Permain–Triassic phase, Kungurian salt was already deforming in the east, whereas Kazanian salt was still accumulating in the center of the basin. Salt structures evolved through several stages in deformation zones that were driven basinward by sediments prograding from the eastern, southeastern, and the southern margins in turn. The second, Jurassic–Neogene phase, involved the development of a basinwide network of polygonal faults above the salt. Throughout this history, the passive growth of huge salt massifs by slow continuous deposition of surrounding sediments characterized the center of the basin. Many of these massifs developed above primary structures in the salt substrate.

During the discussion of Pricaspian geologic history, special attention is given to the processes that move salt. All salt buried by denser strata has some potential to rise by buoyancy, but most overlying strata have the strength to stop the rise of salt indefinitely, unless they are broken and thinned by faults, so that differential loading can drive the rising of the salt (Vendeville and Jackson, 1992; Schultz-Ela et al., 1993; Jackson and Vendeville, 1994). At different times or in different parts, the same salt structure can upbuild through, or increase in relief by downbuilding of strata loading its source layer. Such strata will be referred to as pre-, syn-, non-, or postkinematic overburden. Upbuilding salt structures have sufficient pressure (from buoyancy and/or lateral tectonic forces) to lift or pierce their (ductile) overburdens (Jackson and Talbot, 1994). Thus, upbuilding of salt pillows can arch nonkinematic conformable overburdens and influence subsequent synkinematic strata. Overburdens are unconformable with the contacts of diapirs that can have the shapes of elongate walls or near-cylindrical stocks. Downbuilding is the process where the accumulation of synkinematic overburden buries the salt source layer ever deeper around syndepositional salt structures having crests left near the depositional surface (Jackson and Talbot, 1994, after Barton 1933). In contrast, the crests of upbuilt diapirs actively rise toward the surface. Salt structures that surface can extrude, if either tectonic forces or the

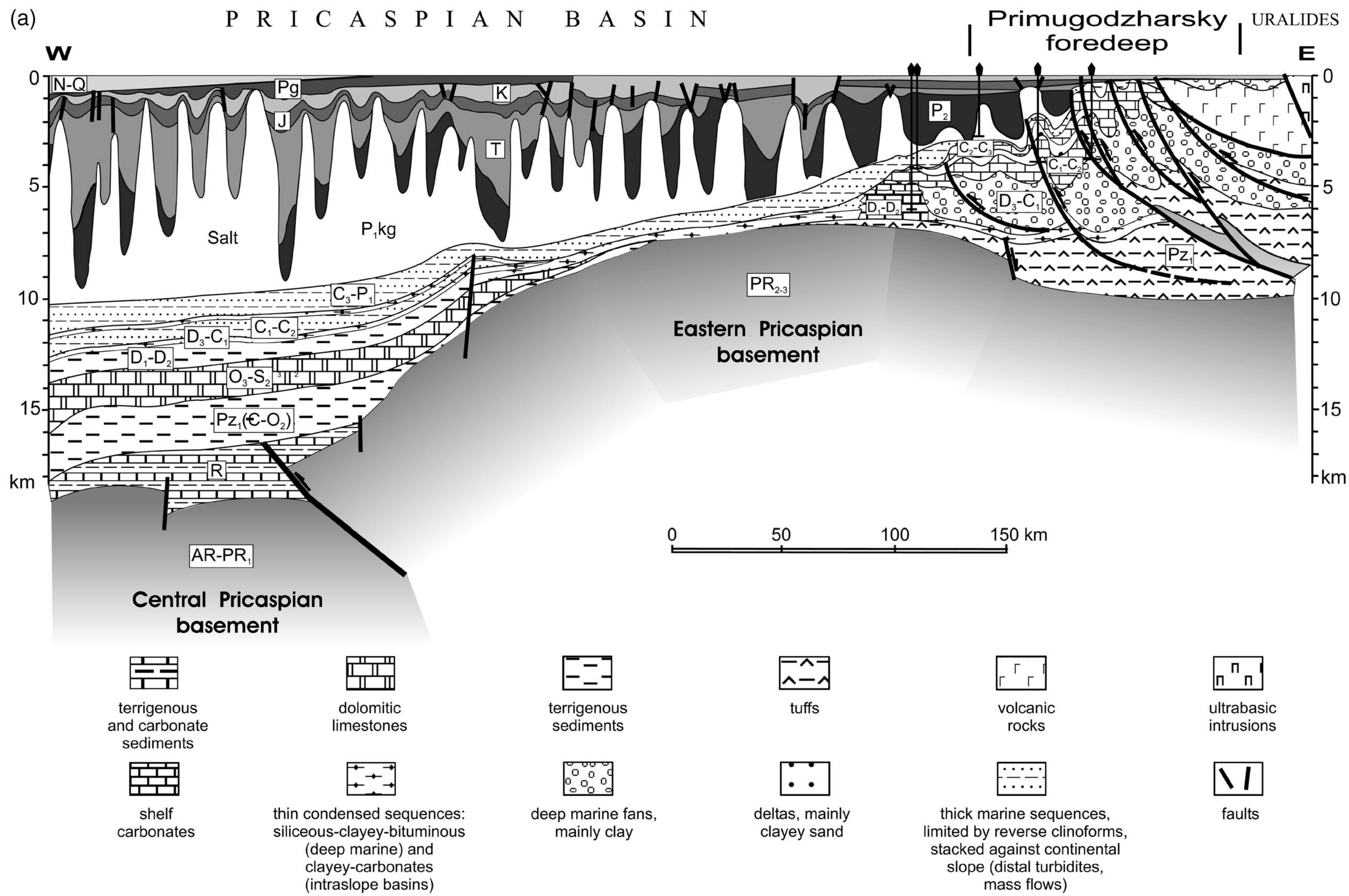


Figure 2. (a) West–east geologic profile (located on Figure 1). Continued.

load of their overburden on the source layer is sufficient. Surface salt structures that extrude faster than they are buried or dissolved can rise above the surface in a salt dome and spread by gravity as submarine and/or subaerial sheet(s) of allochthonous salt. Extruded salt can be buried (with or without subsequent movement) or dissolved (with or without recycling by reprecipitation). To grow or extrude, salt must supply salt structures, but both processes withdraw salt from the source layer. This can lead to the rock above and below the source layer closing to a primary weld between salt structures (that include residual turtleback structures: Volozh et al., 1997b), a process that inhibits further supply of deep salt. Salt structures surrounded by primary welds have lost most of their potential for further growth, unless they are laterally shortened or their stems pinched. We will refer to these structures as starved to distinguish them from potent salt structures that still have the potential for growth because their source layer has not been welded. If faults weakened and thinned overlying nonkinematic strata, a potent salt structure can reactivate and be upbuilt back to the depositional surface by differential loading, where it can grow further by downbuilding, with or without extruding. Buried autochthonous salt can be left in small asymmetric salt rollers (or larger, more symmetrical, salt anticlines) beneath half graben defined by listric down-to-the-basin normal faults near the top of slopes and squeezed into salt anticlines that become walls near the toe of the same slope (Jackson and Talbot, 1994).

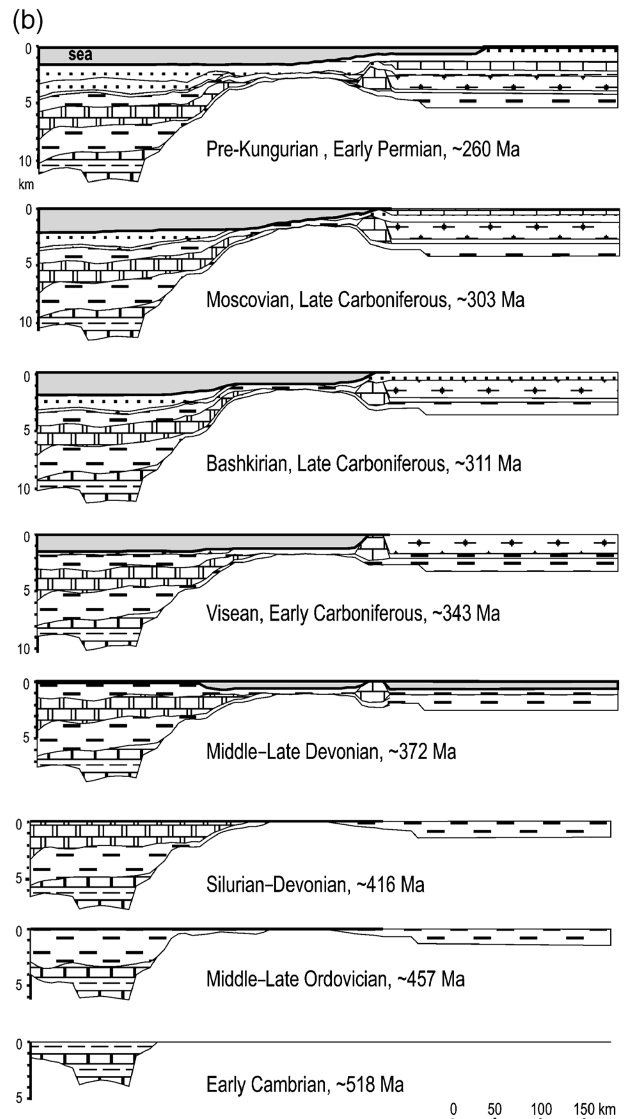


Figure 2. Continued. (b) Its pre-Kungurian evolution backstripped by area balancing [key to lithologies in (a)]. $AR-PR_1$ = Archean to Lower Proterozoic; PR_{2-3} = Middle to Upper Proterozoic; R = Riphean; Pz_1 = Lower Paleozoic; $Є-O_2$ = Cambrian to Middle Ordovician; O_3-S_2 = Upper Ordovician to Middle Silurian; D_1-D_2 = Lower to Middle Devonian; D_3-C_1 = Upper Devonian to Lower Carboniferous; C_1-C_2 = Lower to Middle Carboniferous; C_3-P_1 = Upper Carboniferous to Lower Permian; P_1k_1 = Kungurian, Lower Permian; P_2 = Upper Permian; T = Triassic; J = Jurassic; K = Cretaceous; Pg = Paleogene; N–Q = Neogene to Quaternary.

GEOLOGIC EVOLUTION OF THE PRICASPIAN BASIN

The tectonic basement to the Pricaspian basin consists of Archean–Proterozoic tectonic units joined in Neoproterozoic time by the closure of a pre-Uralian ocean along a (Cadomian) suture that is interpreted to curve southwest–northeast beneath the southeast of the basin (Figure 2a; Volozh, 1991; Brunet et al., 1999).

Pre-Permian Paleozoic Deposition

Pre-Permian strata consist of 2–8 km of lower Paleozoic, Devonian, Carboniferous, and Permian platform sediments that are separated by gentle unconformities (Figure 2). Carbonate reef complexes reaching in relief of as much as 3 km above contemporaneous basinal argillites (Volozh, 1991) trended northward from the southern margin of the basin to well beyond the center of the basin throughout the Devonian (Figures 2b and 3). Lower Paleozoic subsidence over most of the basin was near 1 m/m.y. until it increased to near 50 m/m.y. in the Late Devonian (Brunet et al., 1999). This brief acceleration in subsidence is likely to be

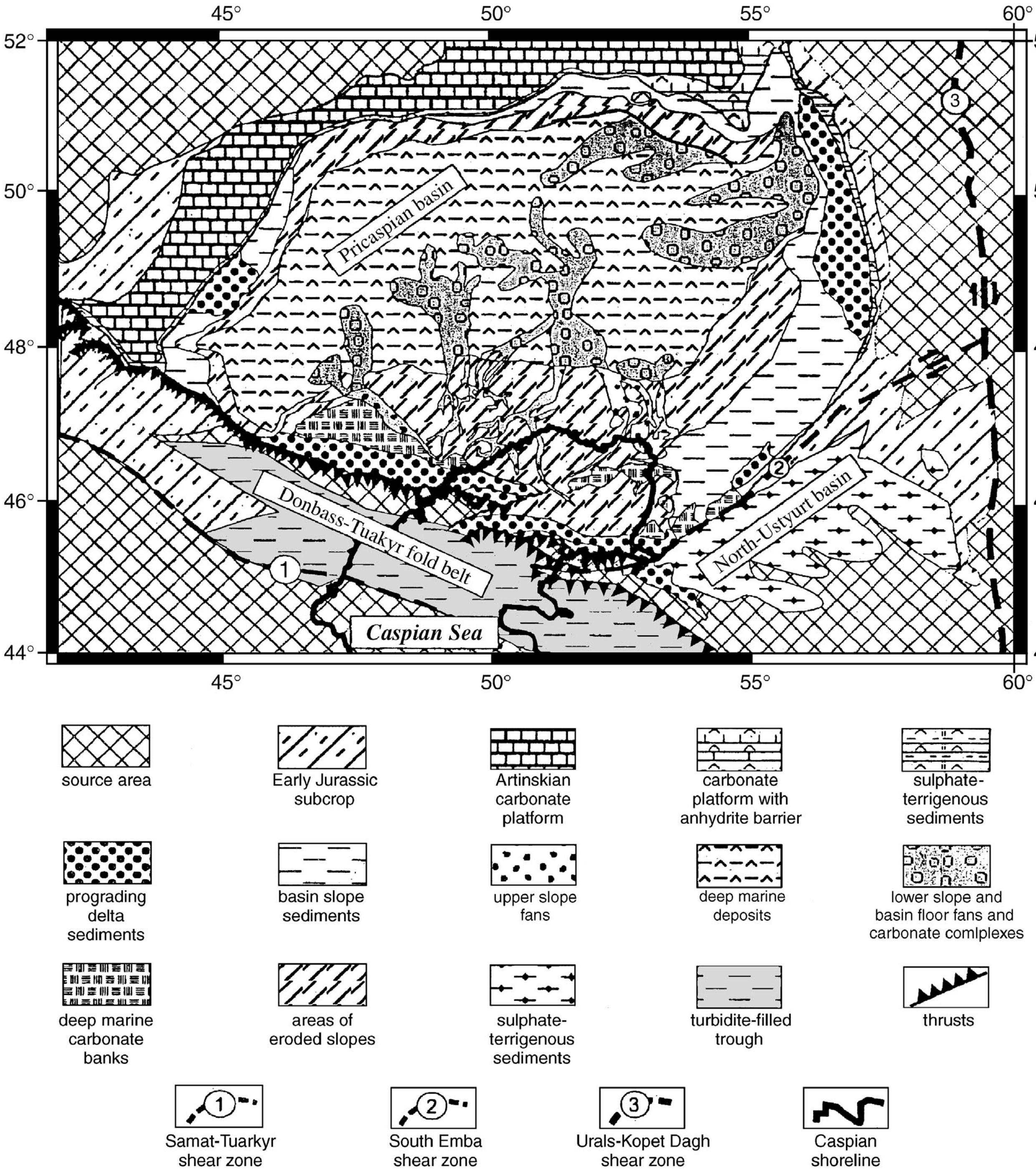


Figure 3. Map of Devonian to Permian lithofacies in the Pricaspian basin.

associated with postrifting phases in the East European platform adjoining the north and west margins of the basin (Ismail-Zadeh, 1998). The reliefs of contemporary carbonate reefs and interbank clinoforms indicate that water depths became more uniform as they deepened slowly (about 1 m/m.y.) during the Late Carboniferous (Figure 2b). The same evidence indicates that Late Carboniferous water depths were approximately 1 km in the Bashkirian (315 Ma) and 2 km by the end of Moscovian (296 Ma). Permian water depths had reached 3 km by the end of the Sakmarian (275 Ma). The end of the Sakmarian had established the present outline of the Pricaspian basin, which changed little until the Paleogene (~60 Ma, see Figure 4).

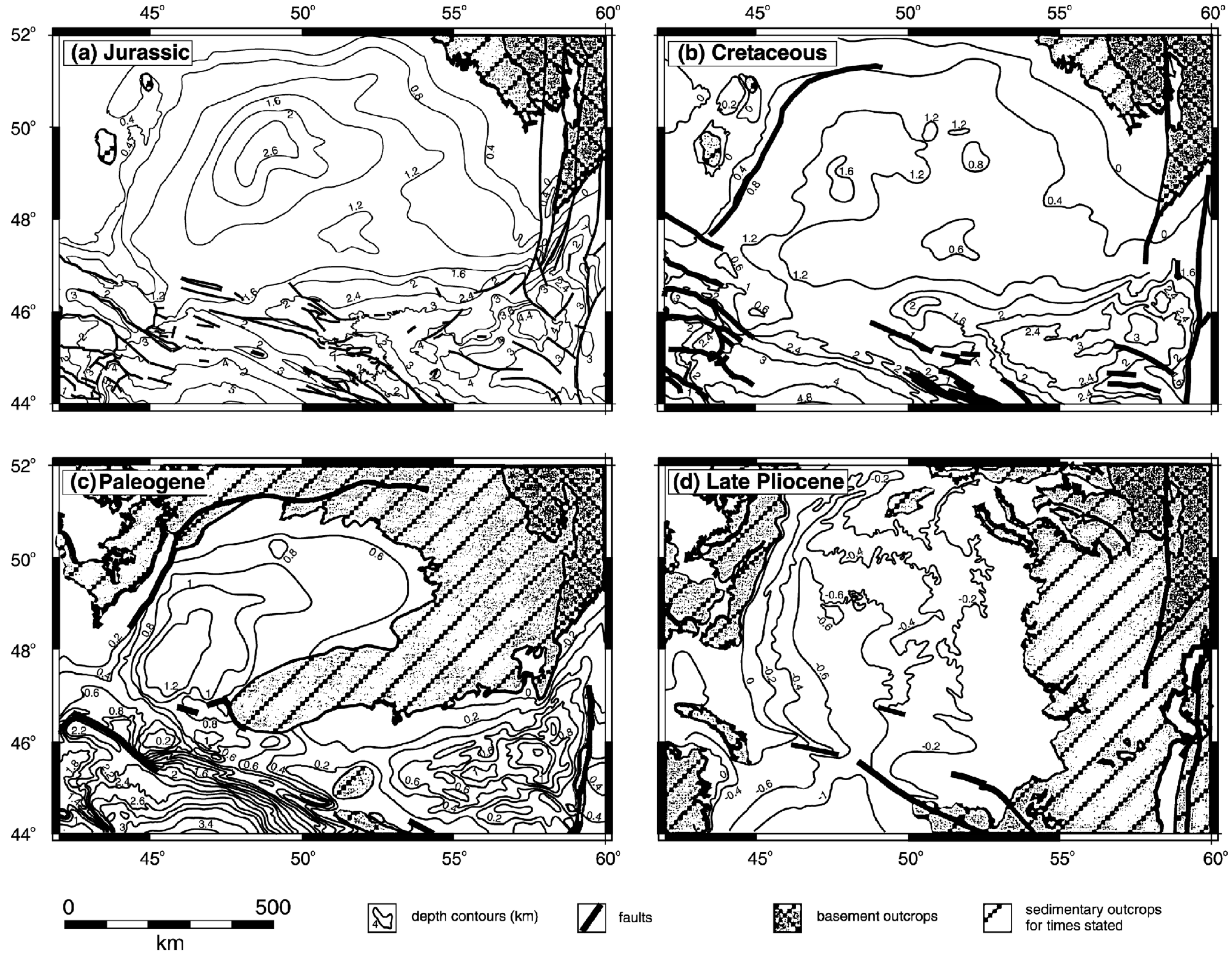


Figure 4. Depth in the current Pricaspian basin of bases of (a) Jurassic, (b) Cretaceous, (c) Paleogene, and (d) upper Pliocene sequences. Deformations are because salt tectonics have been excluded.

Seismic velocities in the terrigenous strata, which are beneath the autochthonous salt and are now buried 5–14 km deep, decrease abruptly from the expected 5–5.2 to 2.8–4 km s^{-1} in all but the eastern margin of the basin. Drilling indicates that such anomalous seismic velocities are related to overpressure in the subsalt strata. Such overpressures could mechanically decouple the above-salt section from thick-skinned lateral forces.

Permian Deposition, Salt Formation, and Movements

During the late Artinskian to early Kungurian (~268–265 Ma, Early Permian), thick deepwater clastic fans were deposited, the sediment being derived from erosion of a continent to the southeast (Figure 3). In Kungurian time (263–258 Ma), the supply of clastic sediments ceased, the climate became arid, and a sequence of thick beds of clean, uniform, marine halite interbedded with thin black shales rapidly buried the fans. This sequence accumulated to a thickness of 2–2.5 km throughout a basin bounded by clastic shore facies to the south and east and 0.5–1-km-thick beds of carbonate and sulfate sediments on shelves to the north and west.

In Kazanian time (258–253 Ma, Late Permian), a cyclic succession of thin halite beds interbedded with shales accumulated until the total evaporite succession reached a thickness of about 4.5 km in the center of the basin. Because the basin still had a marine connection to the southwest, the interbeds are black marine shales in the west, whereas time-equivalent strata in the east are red as a result of terrigenous input from the Urals.

Erosion of the north-south–trending Ural Mountains to the east profoundly influenced Permian to Triassic sedimentation and consequent salt tectonics in the east of the Pricaspian basin. Thus, while Kazanian salt was still accumulating in the center and western part of the basin, clastic sediments sourced from the Ural Mountains were prograding westward into the basin. Loading of the salt by these prograding sediments had downbuilt several rows of inclined walls of Kungurian salt basinward from the eastern margin of the basin by the end of the Permian (see Figure 2, and zone A in Figure 5). Meanwhile, a series of salt rollers having steeply dipping basinward flanks developed beneath the footwalls of down-to-basin, normal, syndepositional faults. The faults define the half graben along the southeastern margin of the Pricaspian basin as their overburden glided downslope (zone D1, Figure 5). At the same time, more symmetrical salt walls hundreds of kilometers long developed in thicker salt beneath the slope along the northern and western flanks of the basin (in zone D2, Figure 5). The reliefs of these salt walls increase progressively from 3 to 5 km basinward, reflecting both basinward thickening of the salt and thin-skinned lateral compression near the toe of the slope. Most of the salt sequence on the northern and western shelves remained essentially passive, but some underwent Late Permian through Triassic down-to-the-basin faulting and block rotation, where the slope instability propagated backward (zone D2, Figure 5).

Triassic Deposition and Salt Movements

By the end of the Permian, transpression in the Ural Mountains had localized to the Urals-Kopet Dagh strike-slip shear zone (Figures 3 and 5 key map) that had accumulated about 700 km of dextral displacement along the mutual border between the Urals and the Pricaspian basin (Khramov, 1991). During the Triassic, the South Emba shear zone trended west-southwest–east-northeast along the southeastern margin of the Pricaspian basin and now sinistrally offsets by about 60 km both a pre-Jurassic deformation front in the west and folds along the western margin of the Urals in the east (Figures 3 and 5 map, Volozh et al., 1999).

The source of terrigenous sediments prograding an arcuate depositional shelf into the basin migrated from the east to the southeast from Late Permian through the Triassic (Volozh et al., 1996). Existing salt structures increased in relief as slope progradation rapidly downbuilt zones of successively younger salt structures basinward, first across zones A to C and then across zone D1 to C (Figure 5). The zones in Figure 5 emphasize how the structures propagated basinward, whereas those in Figure 6 emphasize their present shape. Many of the oldest Late Permian structures in zone A (Figure 5, or zones a_3 and b_2–b_3 in Figure 6) reached high reliefs before they became starved and inactive as the Kungurian salt supplying them closed to primary welds after the Early Triassic. Some deep turtleback structures survive where the primary welds around adjoining salt structures did not meet. Platform sediments showing no sign of salt movement began to bury the crests of starved diapirs in a zone that widened basinward, first from the eastern, and then from the southeastern margins. Reverse faults associated with thick-skinned Ural transpression propagated upward from beneath salt walls that were already inactive (Figure 2a) and alongside asymmetric salt walls that were still growing

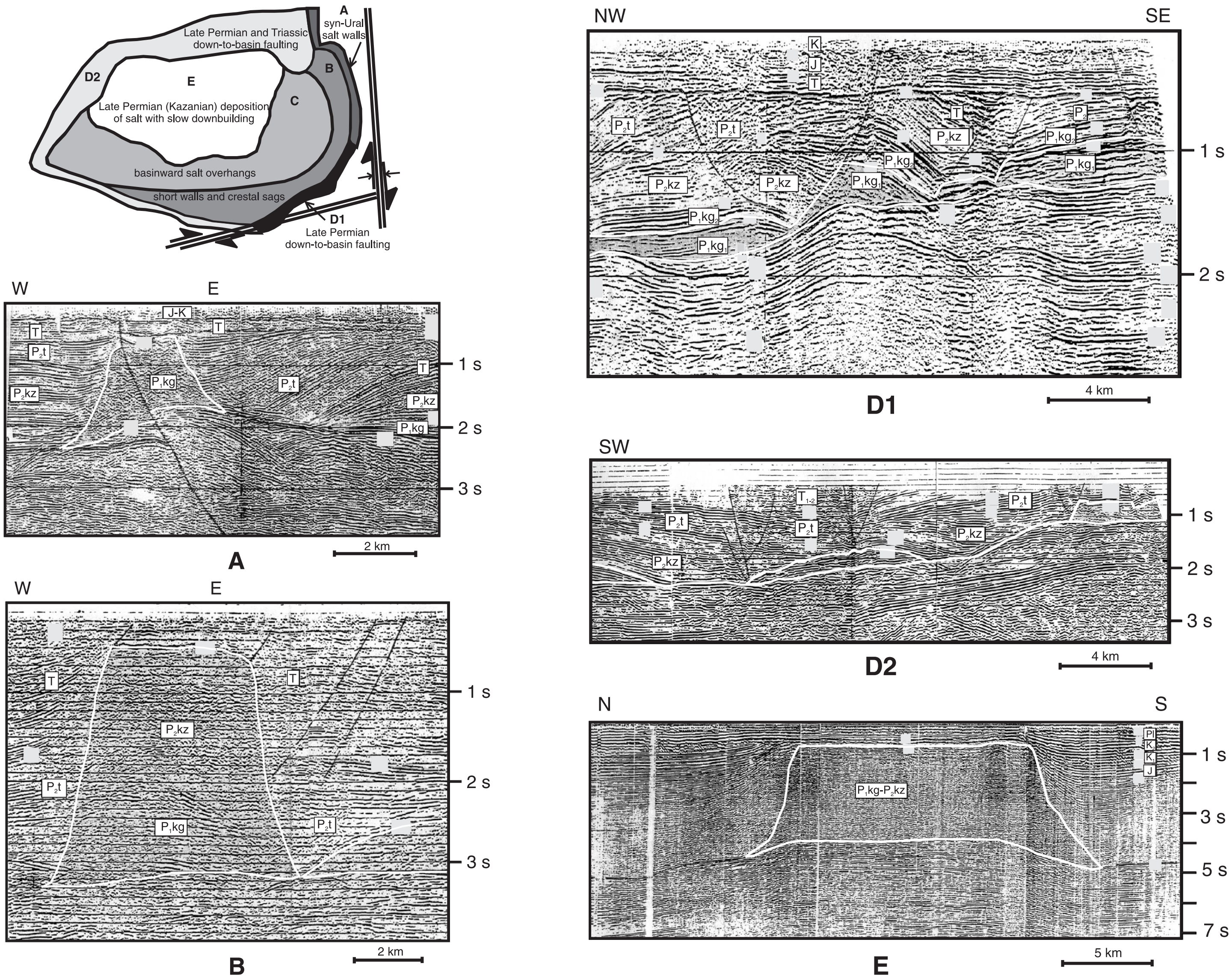


Figure 5. Salt structures in the Pricaspian basin from the Triassic to the Early Jurassic. Upper panel: Sketch map of zones (A–E) having different styles of salt structures. Transpression was transmitted into zone A from the Ural Mountains across a strike-slip shear having about 700 km of dextral displacement. Panels A, B, D1, D2, and E present seismic profiles (located in Figure 1) showing structures in salt across zones indicated. Seismic profiles illustrating structures in salt across zone C are shown in Figures 7, 12, and 13. P_1 = Lower Permian; P_1kg = Kungurian; P_1kg_1 = lower Kungurian; P_1kg_2 = upper Kungurian; P_2 = Upper Permian; P_2kz = Kazanian; P_2t = Tatarian; T = Triassic; T_{12} = Lower to Middle Triassic; J = Jurassic; J–K = Jurassic to Cretaceous; K_1 = Lower Cretaceous; K_2 = Upper Cretaceous; Pl = Paleogene.

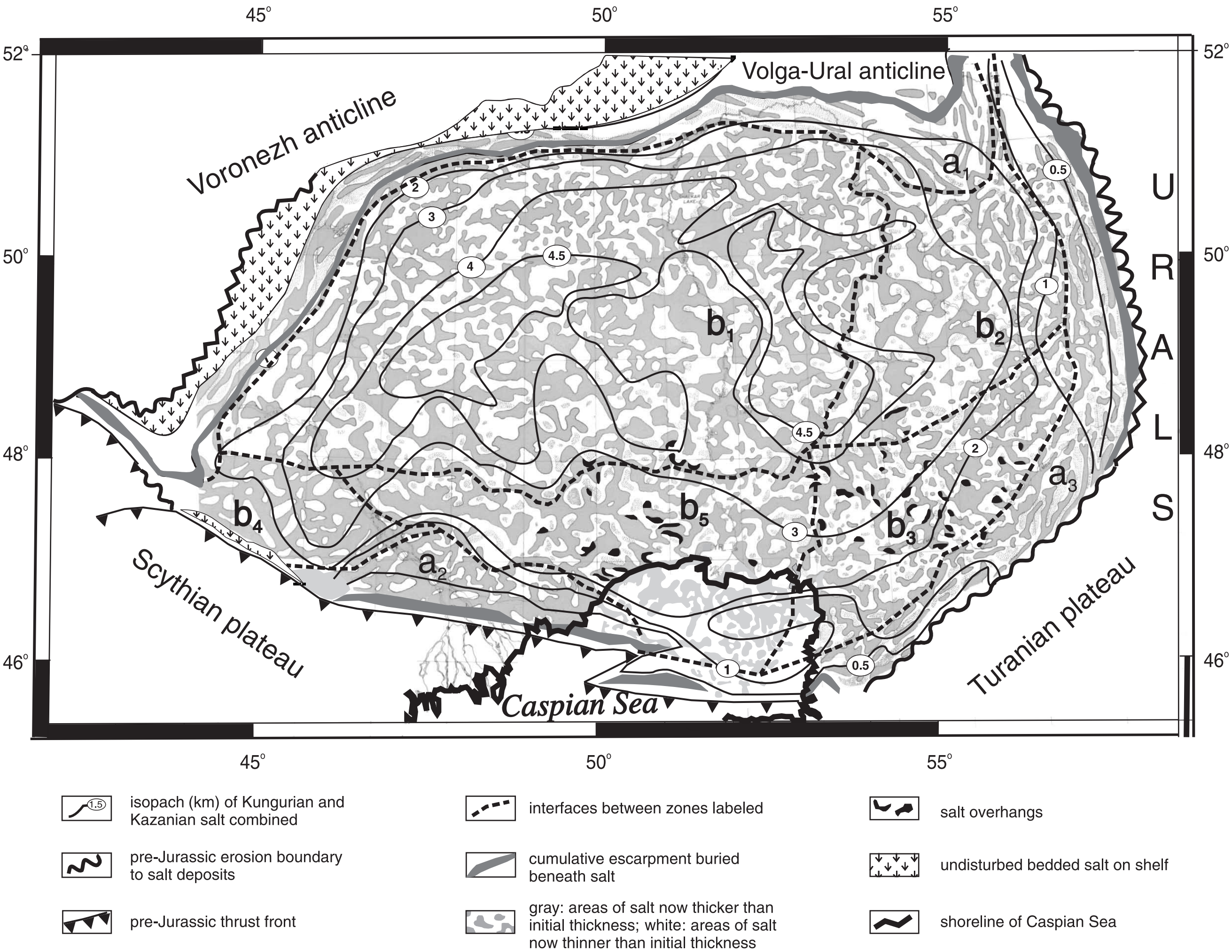


Figure 6. Map of Pricaspian basin showing current shapes of salt structures. Zones having various shapes of salt structure: a_1 and a_2 = equidimensional and wall-like pillows of Kungurian salt; a_3 = rollers, anticlines, and turtlebacks of Kungurian salt; b = walls and domes where b_1 = halokinesis involved both Kungurian and Kazanian salt; b_2–b_5 = halokinesis involved only Kungurian salt; b_2 = diapiric by the end of the Permian; b_3 = diapiric by the end of the Triassic; b_4 = diapiric by the end of the Jurassic; b_5 = not yet diapiric, but some have surfaced and extruded or been recycled. Notice that some of the boundaries between current styles of salt structures here tend to correspond to boundaries to the subsalt Lower Permian lithofacies on Figure 3.

during sedimentation along the western side of zone A (Figure 5).

In zone B (Figure 5), the crests of some of the salt stocks and short salt walls developed Triassic sag basins that were elongated north–south (Figure 7). Crestal sag basins between salt cusps suggest lateral extension (Vendeville and Jackson, 1992). Although sedimentation in some of the sag basins in zone B appears to be contemporaneous with the last of the transpressional reverse growth faults beneath the shelf in zone A (see Figure 5), crestal sag basin formation is interpreted as contemporaneous with down-to-the-basin normal growth faulting further basinward in zone C (Figure 5). As in zone B, continued basinward migration of the depotrough through zone C downbuilt a succession of huge asymmetric salt stocks.

In contrast to the vigorous sediment progradation from the eastern and southeastern margins of the Pricaspian basin, the northern and western margins remained comparatively starved of clastic sediment and were bordered by carbonate and/or sulfate shelves until Kazanian time (zone D2, Figure 5). Salt and overlying strata are characteristically flat lying and undeformed shelfward of a marginal zone of (mainly) down-to-the basin faults (zone D1, Figure 5).

In the basin center beyond the slowly encroaching shelf (zone E, Figure 5), slow, essentially continuous sedimentation that kept pace with basin subsidence from the Early Triassic through the Cretaceous downbuilt huge salt massifs. These have reliefs ranging from 3 to 8 km and horizontal dimensions of about 100 km without any significant overhangs having been recognized (zone E in Figure 5, zone b_1 in Figure 6). The earliest and largest of these salt massifs developed above the early Kungurian clastic fans beneath the salt (Figure 3). Slightly smaller and younger structures commonly surrounded larger massifs.

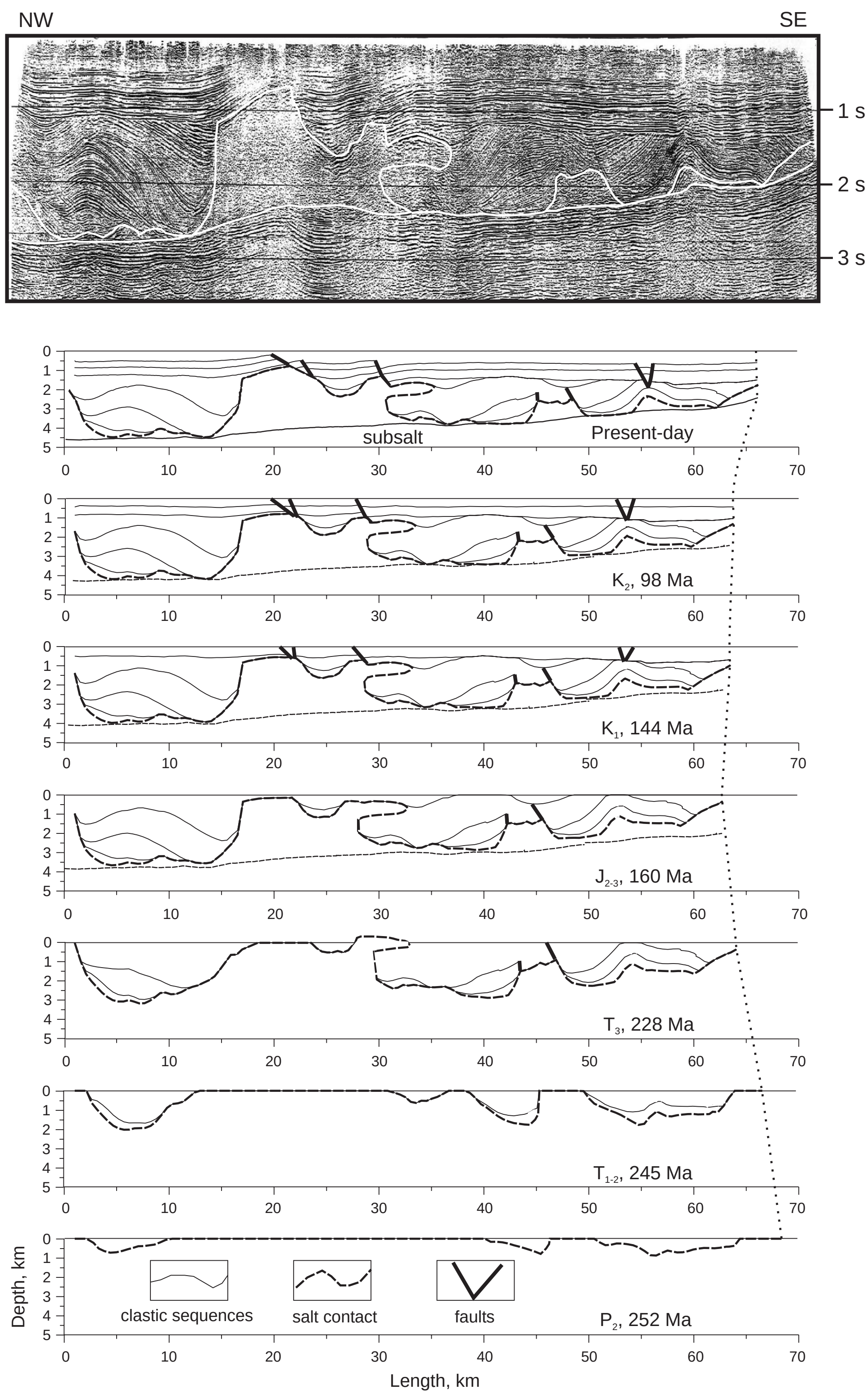


Figure 7. Seismic profile (located in Figure 1) and restoration to stated times. Dotted line along right-hand end of restored profiles indicates changing profile length by area balancing.

Jurassic Deposition and Salt Movements (Mainly Extrusion and Overhangs)

During the Early Jurassic (Hettangian and Sinemurian, ~208–198 Ma), another wave of salt diapirism migrated into the basin, now from the southern boundary (zones D2 to C in Figure 5 key map, from a_2 to b_4 in Figure 6). Initiation of this wave is attributed to downbuilding by clastic sediments prograding from the active Donbass-Tuarkyr fold belt beyond the southern boundary of the basin, but it continued to propagate northward during the Middle Jurassic in response to lateral shortening (Figures 3, 4a).

This folding and the more general Early Jurassic (Cimmerian) uplift attributed to the closure of paleo-Tethys and the resulting Cimmerian convergence (Alexander et al., 2000) led to an approximately 35-m.y. hiatus (Figure 8). This hiatus is generally represented as an Upper Triassic–Middle Jurassic disconformity but is expressed as an angular unconformity in the vicinities of still-active salt structures. Some Late Permian to Early Triassic pillows of Kungurian salt deflated to drive diapirs that surfaced in association with Jurassic growth faults (Figure 4a).

Many of the diapirs in Zone C (Figure 5 key map) have significant overhangs (Figures 6, 7, 9–11) that we interpret as sheets of allochthonous (Kungurian) salt that extruded over the surface, likely accompanied by some recycling by dissolution and recrystallization. Backstripping of profiles of salt structures (e.g., Figures 7, 9, 10; Ismail-Zadeh et al., 2001b) indicates that many were not only at the surface in and after the Late Permian but extruding above it, particularly during the Late Triassic–Middle Jurassic depositional hiatus, and that some were still extruding until the Late Jurassic. One of the youngest sheets of allochthonous salt so far recognized in the Pricaspian basin was also the longest, that at Kum (Figure 9). This salt formed a pillow from Middle Permian through Triassic times after the salt structure immediately to the west had already surfaced. The crest of the Kum salt diapir appears to have been at, or close to, the surface from the Late Permian to the Late Jurassic (Figure 9). The column of Permian to Upper Jurassic strata (density = 2600 kg m^{-3}) loading the salt source (density = 2200 kg m^{-3}) was only 1.6 km high. Balancing forces (density of salt × gravitational acceleration × height of salt column = density of overburden × gravitational acceleration × height of column of overburden) implies that gravity alone could have supported a salt column with a level of neutral buoyancy only 0.3 km above the surface. Studies of salt extrusions at different stages of development in Iran indicate that where salt extrudes faster than it dissolves and where deposition of overburden is slow (or negative), extruding salt rises to its level of neutral buoyancy in an extrusive dome that then spreads into a sheet of allochthonous salt (Talbot, 1998). By the Late Jurassic, progressive squeezing of autochthonous salt from depth (Figure 9) had extruded a sheet of allochthonous salt at Kum that reached a thickness approaching 1 km and an east–west length of 14 km; it is not clear whether this extrusion was submarine or subaerial, and there is no known associated oil (Volozh et al., 1994). Rapid deposition of Upper Jurassic to Lower Cretaceous nonkinematic strata buried the extruded salt sheet at Kum, but subsequent deposition reactivated and upbuilt the diapir feeding it and also led to the allochthonous salt sheet upbuilding a salt pillow (Figure 9).

As extrusion starved increasing numbers of diapirs, the zone of starved salt structures in zones B and C (Figure 5) widened behind a basinward-migrating zone of salt structures that were still active. Many of these active structures in zone C (Figure 5) extruded from deeper levels than Kum (e.g., Figures 7, 10, 11). Consequently, these could have risen much higher than 0.3 km and rivaled the currently active salt fountains of Iran, which rise to as much as 1 km above their bedrock orifices (Talbot, 1998). Numerical models tuned to the dimensions and measured velocities of extrusion of one of the largest Zagros salt fountains (Talbot et al., 2000) suggest that the salt of this fountain has been extruding from its bedrock orifice at rates near 1 m/yr for approximately 56,000 yr, the time estimated to exhaust its local source layer. We consider the Iranian salt fountains to be modern analogs of many salt structures in the Pricaspian basin from the Late Permian to Middle Jurassic.

None of the salt overhangs in the Pricaspian basin approach the dimensions of the large salt nappes in the Gulf of Mexico (e.g., Worrall and Snelson, 1989). We attribute this to basin configuration. In the Gulf of Mexico, rapid sedimentary progradation results in salt nappes that spread downslope by gravity toward an open ocean basin. By contrast, the Pricaspian basin was always closed, and salt extrusions there had no open continental slope toward which they could gravitate.

The current geometry of the approximately 1800 salt structures known in the Pricaspian basin is summarized in map form in Figure 6 and in table form in Figure 8. Salt structures form an unusually high proportion of the area of the Pricaspian basin, particularly at the Jurassic subcrop, which is generally less than 2 km deep.

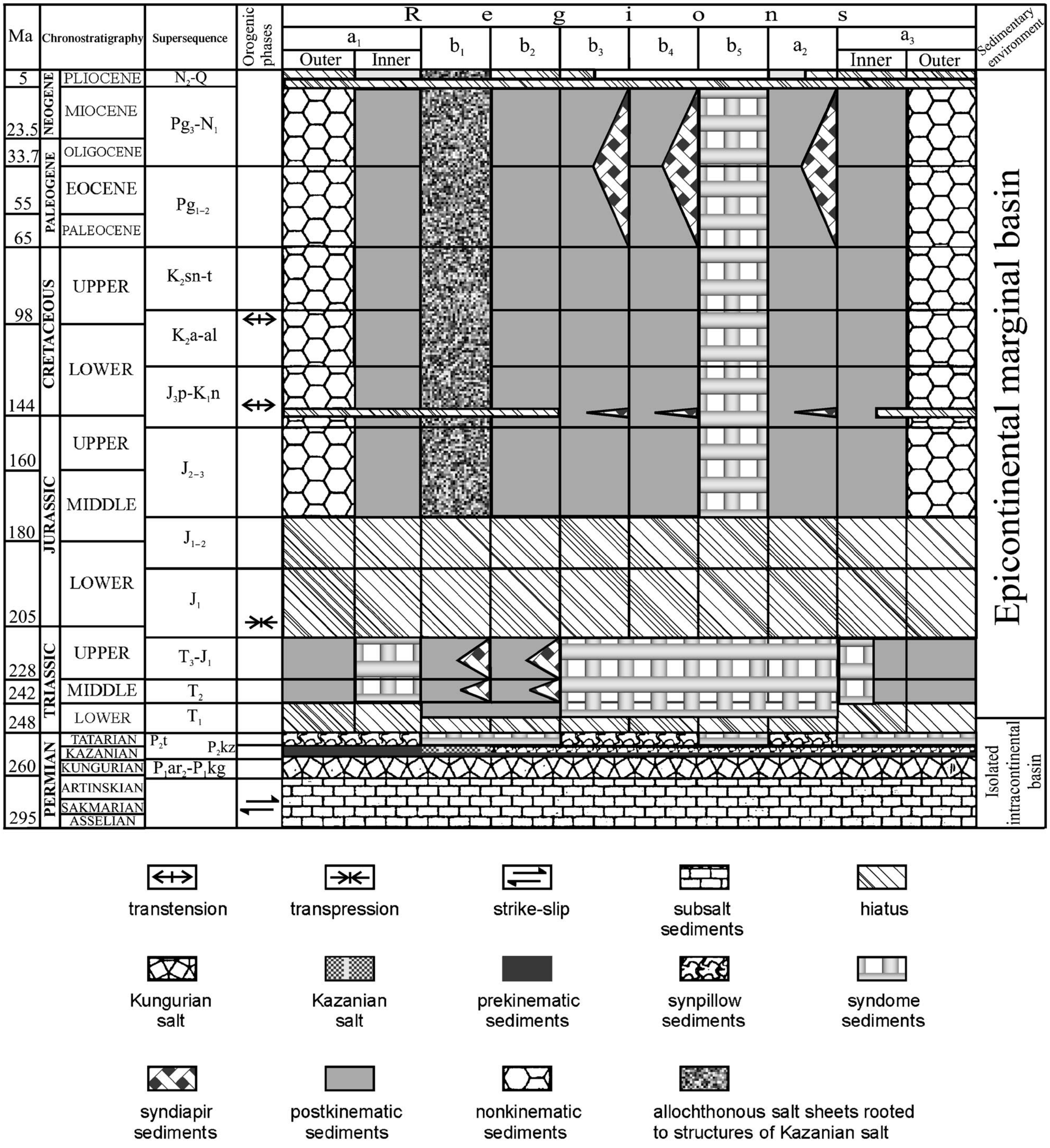


Figure 8. Summary of sedimentation and halokinesis in the Pricaspian basin. Regions a_1–b_5 are identified in Figure 6.

Jurassic–Paleogene Deposition and Polygonal Faults

A pattern of polygonal grabens and half grabens connects preexisting salt structures throughout most of the basin (Figure 12) and is interpreted here as having initiated during the Early Jurassic (Cimmerian) uplift and the extrusion of large volumes of salt withdrawn from depth during the consequent hiatus. When subsidence resumed, deposition throughout the basin was of shallow-water Jurassic to Paleogene argillites, sandstones, and thin carbonate beds. A minor discontinuity near the Jurassic-Cretaceous boundary (Figure 8) might be associated with localized uplift because of collisional events along the southern margin of Eurasia (Alexander et al., 2000).

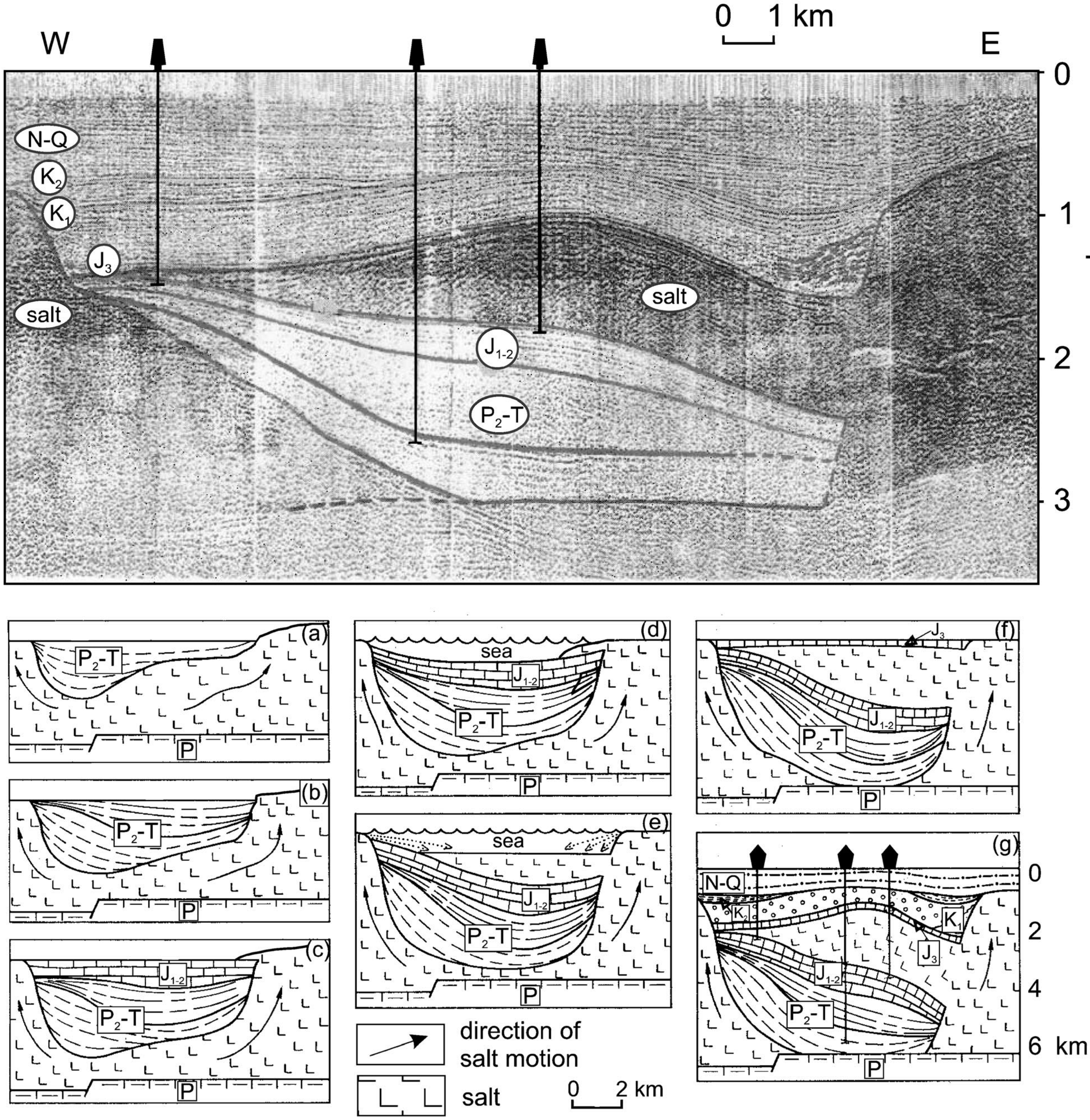


Figure 9. The sheet of allochthonous Kungurian salt at Kum (located on Figure 1) was extruded in the Late Jurassic and began to upbuild during the Paleogene (modified after Volozh et al., 1994, Figures 7, 8). Upper panel: seismic profile showing the Kum overhang. Bottom panel: evolution sketches of the Kum overhang (a–g). P = pre-Kungurian substrate; P_2–T = Middle Permian to Triassic; J_{1-2} = Lower to Middle Jurassic; J_3 = Upper Jurassic; K_1 = Lower Cretaceous; K_2 = Upper Cretaceous; N–Q = Neogene to Quaternary.

Jurassic to Paleogene sediments that buried starved salt structures are postkinematic and flat lying with a uniform thickness between 2.1 and 2.5 km. Contemporaneous sediments deposited over potent diapirs are synkinematic and deformed by narrow asymmetric salt walls or stocks, most in the hanging walls of normal growth faults. We infer that the faults weakened and thinned any overburden that had onlapped exposed still-potent Permian–Triassic salt structures. These structures reacted by actively upbuilding back to the depositional surface and resuming downbuilding. Diapiric salt walls and stocks that were downbuilt throughout

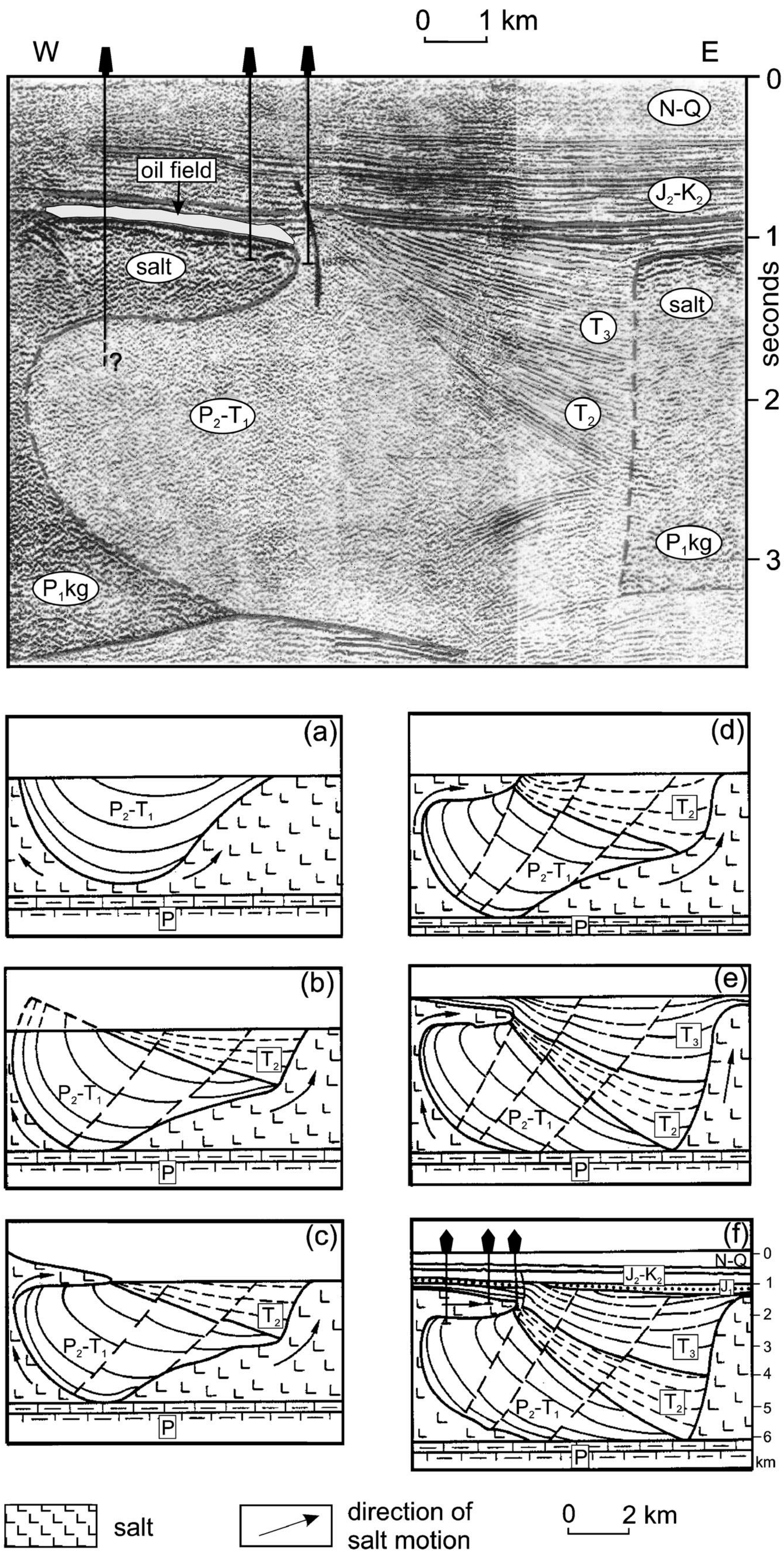
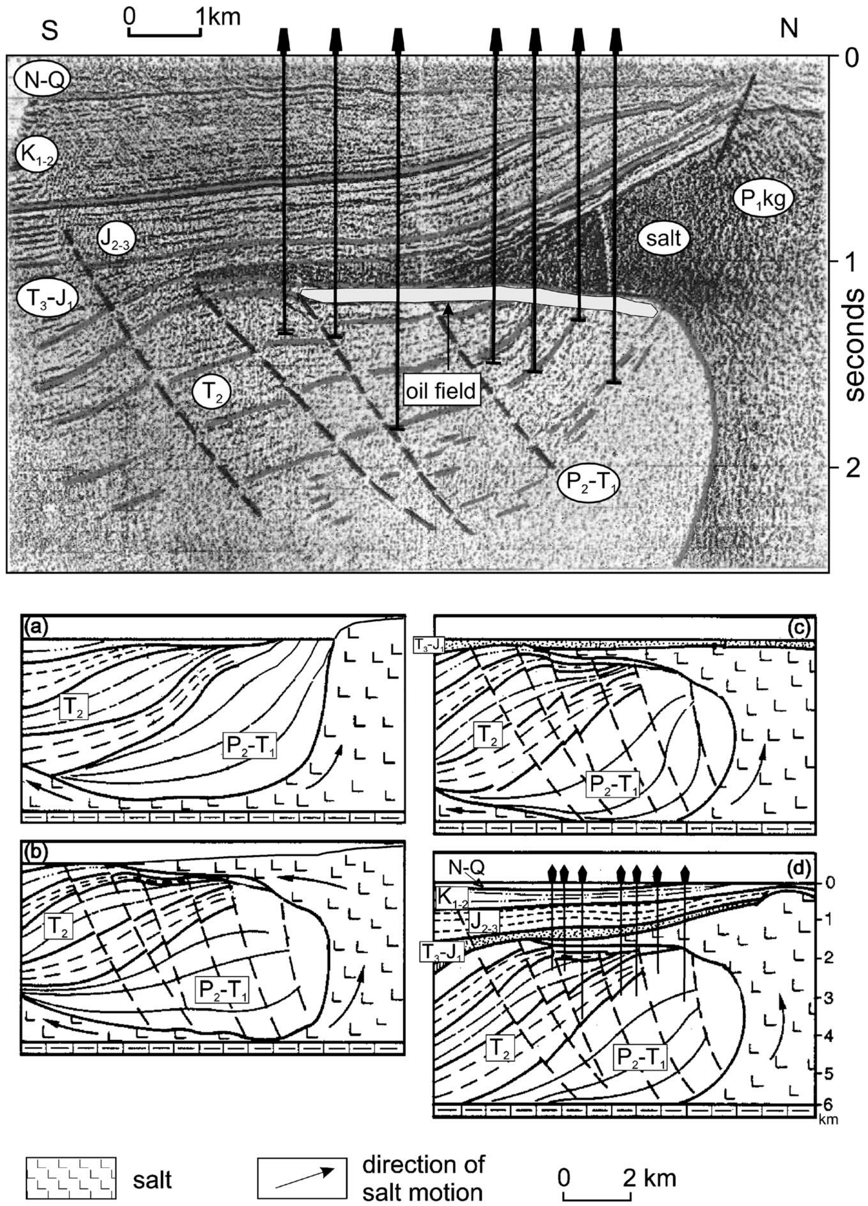


Figure 10. The Kotyrtas North oil field (located on Figure 1) is trapped above a sheet of allochthonous Kungurian salt extruded in the Middle Triassic (modified after Volozh et al., 1994, figures 2, 4). Upper panel: seismic profile showing the Kotyrtas North overhang. Bottom panel: evolution sketches of the Kotyrtas North overhang (a–f). P = pre-Kungurian substratum; P_1kg = Lower Permian (Kungurian); P_2–T_1 = Middle Permian to Lower Triassic; T_2 = Middle Triassic; T_3 = Upper Triassic; J_2–K_2 = Middle Jurassic to Upper Cretaceous; N–Q = Neogene to Quaternary.

Figure 11. A sheet of allochthonous Kungurian (±Kazanian salt) extruded in the Middle to Late Triassic trapped the Novobogatinsk oil field (located on Figure 1) (modified after Volozh et al., 1994, figures 5, 6). Upper panel: seismic profile showing the Novobogatinsk overhang. Bottom panel: evolution sketches of the Novobogatinsk overhang (a–d). T_3–J_1 = Upper Triassic to Lower Jurassic; J_{2-3} = Middle to Upper Jurassic; K_{1-2} = Lower to Upper Cretaceous. See Figure 10 for other notations.



the Jurassic to Paleogene are symmetric in profile and surrounded by overburdens with uniform thickness.

The faults in the laterally isotropic polygonal network display a wide range of orientations and degrees of connectivity (Figure 12). Complex polyhedra defined by faults are typically 5–20 km across and involve strata having regional dips of less than 1° and thicknesses between 2.1 and 2.5 km. Line balancing along profiles having a wide range of orientations indicates that lateral extension across the faults averages approximately 5% in all horizontal directions. The faults are curved in plan (Figure 12) and more or less listric in section. Fault pairs defining a graben are seldom symmetric. Some converge downward to intersect near the base of the Jurassic (which can be thrown by as much as 0.6 km). More converge at the crests of potent Permian–Triassic structures of Permian salt that reactivated and grew from Jurassic to at least Paleocene; some are still active.

As in other documented polygonal fault systems (Henriet et al., 1991; Verschuren, 1992; Cartwright and Lonegran 1996; Walsh et al., 2000; Watterson et al., 2000), most fault traces in the Pricaspian basin follow the axes of polygonal anticlines (Figure 12), are confined to a few stratigraphic intervals of post-"rift" basin infills, and include growth faults that reach the depositional surface. Polygonal systems of normal faults (Figure 12) point to isotropic lateral extension. No independent evidence for either lateral extension of the Pricaspian

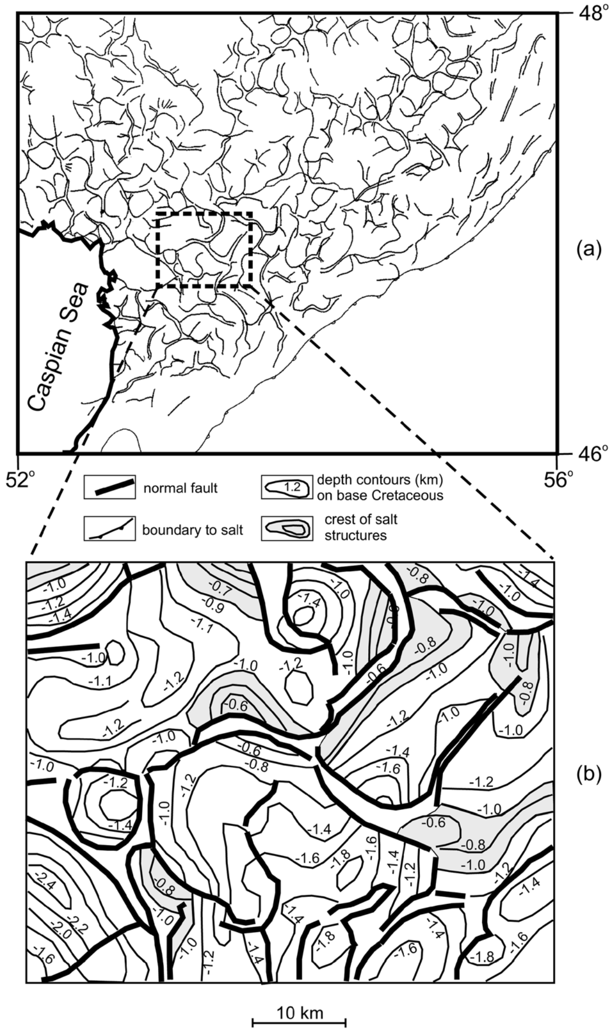


Figure 12. Maps of part of the southern Pricaspian basin (upper map located in Figure 1) showing normal faults offsetting base Cretaceous.

region or uplift of the magnitude that could account for the calculated 5% isotropic extension exists. Even an uplift of 2 km would result in only 0.0314% lateral extension (Price, 1966).

Most polygonal fault patterns have been attributed to a gravity-driven mechanism instead of lateral tectonic forces (e.g., Ismail-Zadeh et al., 2002). Most of the above references invoke density inversions at the base of the faulted system, but Cartwright and Lonegran (1996) cited volumetric contraction during compactional dewatering of mud-dominated intervals. Compactional dewatering is not likely to have been particularly significant in the Pricaspian basin, where the polygonal fault system developed in sediments that were not dominated by argillites. Instead, most faults rooting to the crests of reactivating structures of low-density salt implicate gravitational forces. The only part of the Pricaspian basin missing polygonal faults is along the eastern margin (Figure 12), where salt structures had been starved by the end of the Triassic, and fluids beneath the deep Kungurian salt layer lost their usual overpressures along Ural-related thrusts (Figures 2a and 5, zone A).

We attribute the polygonal fault system in the Pricaspian basin to gravity having reactivated large salt structures that still had the potential for growth in smaller structures when they were buried further. Although it involves apparently brittle faults, the polygonal pattern is like the shallow levels of spoke patterns of gravity overturn modeled in ductile materials by Talbot et al. (1991, see Watterson et al., 2000) and Ismail-Zadeh et al. (2000). This comparison implies that the estimated 5% lateral extension might be confined to above polygonal salt uplifts and compensated on a basin scale by equivalent isotropic shortening across the intervening salt-withdrawal basins. Despite involving brittle faults in the top 2.5 km, the pattern involved withdrawal of salt from an autochthonous source layer about 5–10 km deep (Figure 2a). The brittle deformation pattern at shallow levels in the Pricaspian basin is therefore attributed to ductile flow of salt and overburden deeper in the unstable section.

In every other documented example of the polygonal fault system, polygonal normal faults near the top boundary directly overlie polygonal uplifts near the bottom boundary. This implies simple prismatic polygonal movement cells, very different from the complex spokes movement patterns modeled in very unstable sections by Talbot et al. (1991), in which polygons near the top boundary are offset half a wavelength from those near the bottom boundary. By analogy with thermal convection (Talbot et al., 1991; Ismail-Zadeh et al., 2001a), gravity drives stronger density instabilities in movement patterns that are more complex than the simpler movement patterns driven by weaker density instabilities. The generally simpler Jurassic to Paleogene movement cells obvious in the Pricaspian basin were smaller in scale and complicated by inheriting aspects of the more complex and larger scale Permian–Triassic gravity structures.

Cenozoic Deposition

Sedimentation was slow in the intracontinental Pricaspian basin during the Late Cretaceous but increased during renewed Paleogene subsidence. Many of both the potent Permian–Triassic salt structures and their narrower Jurassic to Paleogene upward extensions reactivated in Neogene times so that they upbuilt and lifted local overburden (Figures 7, 9).

During the Neogene, decreasing numbers of salt-withdrawal basins localized to the margins of still-potent salt structures. Most such basins tend to be deep and aligned (e.g., 20 × 5 km) along northeast–southwest faults in the basement that reactivated beneath the margins of salt massifs in a central region now characterized by low relief and saline lakes. Some of the sheets of allochthonous salt emplaced in the Triassic and Jurassic in zone C (Figures 5 key map and 6, zones b_3 and b_4) upbuilt short-wavelength pillows in the Late Cretaceous and/or Neogene (e.g., Figure 9).

The geography of the Pricaspian basin changed dramatically during the Pliocene, as a deep basin developed in the area of the South Caspian Sea (Figure 13) (Devlin et al., 1999). Subsidence kept pace with the rapid accumulation of 5–8 km of Pliocene sediments (which serve now as the main hydrocarbon reservoir rocks in the basin), so that the South Caspian lake remained shallow (Reynolds et al., 1998; Knapp et al., 1999). Sediments in the eastern half of the basin were red-brown terrigenous clastics supplied from the paleo-Amu-Darya river in the east (Figure 13). Those in the western South Caspian basin were gray organic-rich clastic rocks supplied from the paleo-Volga river (Figure 13). Early Pliocene sedimentation bypassed the former Pricaspian basin through southward-trending canyons incised to depths of 0.7 km in Cretaceous platform strata. The paleo-Volga river draining to the base level provided by the South Caspian lake having a surface about 1 km below ocean level eroded these structures (Antipov et al., 1996). The bases of these early Pliocene canyons truncated the tops of the shallowest salt diapirs. Coarse clastic sediments filled the canyons as the lake level rose and transgressed north of the former Caspian basin by the end of the Messinian, about 3.8 Ma (Antipov et al., 1996).

HYDROCARBONS IN THE PRICASPIAN BASIN

Salt at the base of the Kungurian sequence is now at 170°C in the center of the basin and 60°C around the margins (Kalinko, 1991). Thermal gradients are about 10°C/km in the salt and 25–30°C/km in the surrounding sediments (Zhevago, 1972; Sidikov, 1977). Such gradients imply that the complete Pricaspian basin is still in the oil window, including the flat-lying Riphean to Carboniferous shelf sediments beneath the Permian salt and now at depths reaching 10 km (Figure 2a). Three separate hydrocarbon sources can be distinguished.

Pre-Kungurian shales sourced a first generation of sulfurous oil that collected in the carbonates beneath the salt. This oil started rising through the primary salt welds in the Jurassic and was trapped in reservoirs of Upper Permian to Cenozoic terrigenous rocks associated with salt overhangs extruded during phases of slow deposition from the Triassic to end of the Jurassic. Such oil may also have been trapped in pinch-outs against the central massifs (zone E, Figure 5) and basin-marginal prerafts (zones D1 and D2, Figure 5). This is the only oil known above the salt northwest of the axis of shallow Cretaceous rocks across the Pricaspian basin (Figure 4b).

A second generation of oil was sourced from thick Jurassic argillaceous graywackes more than 3 km deep in a basin to the southeast and flushed more than 150 km northwestward after it connected with the Pricaspian basin in Cretaceous time (Figure 4b). This oil is sweet and was trapped in structures over Cenozoic diapirs of Kungurian salt, many of which are still active. This light oil did not cross the axis of shallow Cretaceous rocks across the basin (Figure 4b) and so is found in the general region of salt overhangs (Figure 6); however, exploration has been confined to fault traps in the nonkinematic overburden above such reactivated salt diapirs. A typical example of an oil pool in this area is 150 m thick and 4–5 km long in multiple reservoirs of Jurassic and Cretaceous sandstone beneath caps of terrigenous shales at high points in uptilted strata in the footwalls of crestal graben.

Shales capping the clastic infills of the huge Pliocene canyons trapped a third-generation hydrocarbon, methane in solution in overpressured groundwater, in the south of the Pricaspian basin (Figures 4d, 13). These are thought to be sourced from the south.

The next section describes representative examples of fields in two of the three generations of hydrocarbons in the Pricaspian basin.

Examples of Hydrocarbon Fields

The Kotyrtas North oil field (Figure 1) is an example of pre-Kungurian oil trapped in Middle Triassic strata that onlapped an overhang of Kungurian salt by Neogene shales above and normal faults updip. The salt overhang extends at least 4 km over steep Permian–Lower Triassic sediments along a width exceeding 8 km (Figure 10).

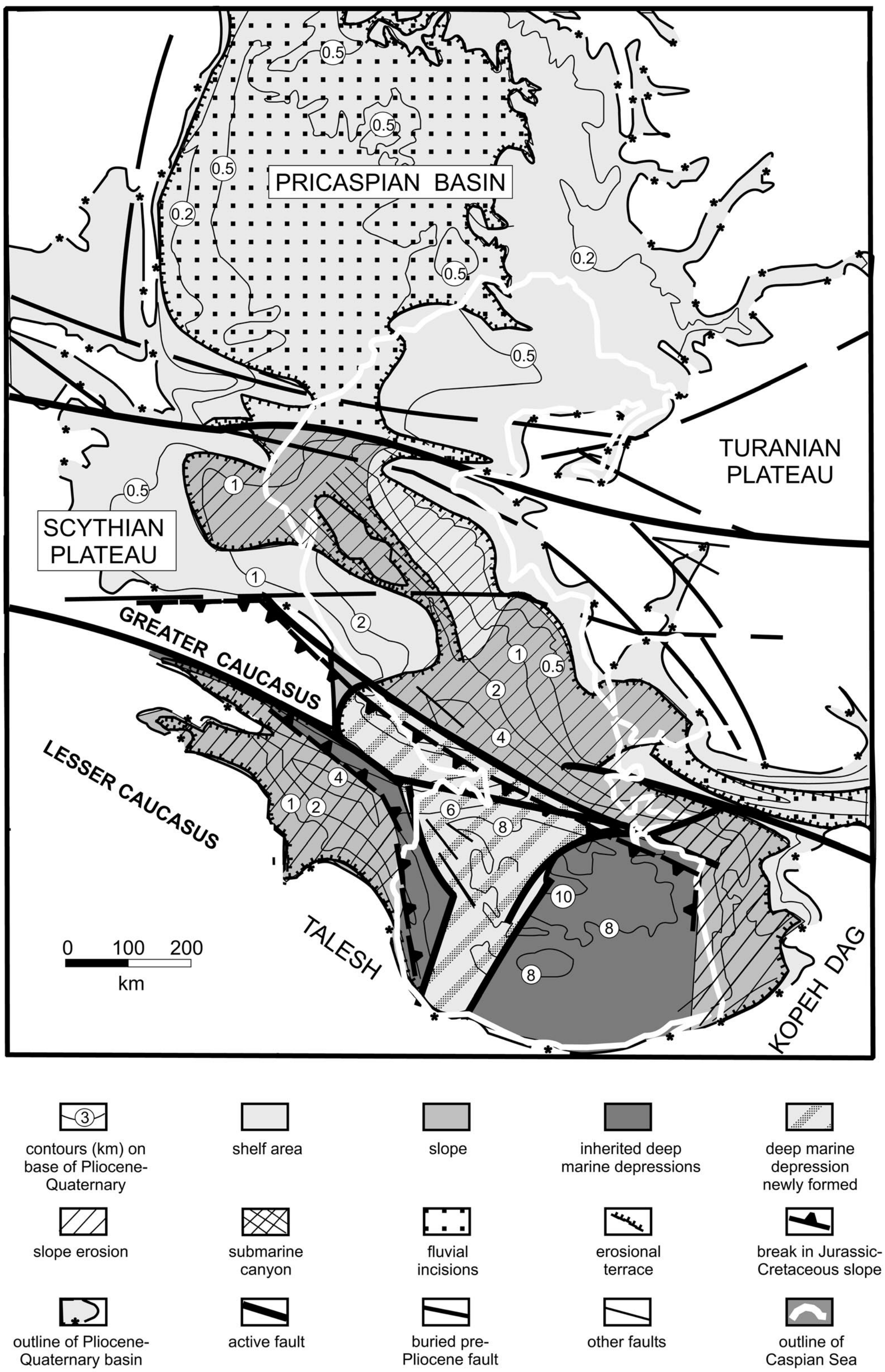


Figure 13. Structural map of the Pricaspian basin in Pliocene times illustrating incisions and canyons eroded through Cretaceous platform sediments by the paleo-Volga and paleo-Amu-Dariya rivers draining into the South Caspian lake having a surface about 1 km below ocean level (modified after Antipov et al., 1996).

Because no hydrocarbons are expected to have been generated in the terrigenous Permian–Triassic red beds, the low-sulfurous oil in the Kotyrtas North field ($S = 0.36–0.76$ wt.% S) is thought to be pre-Kungurian (Devonian–Lower Permian). The oil was driven through the primary weld, where the differential load on overpressured subsalt fluids was greatest close to the stem of the salt stock (Figure 10). The only well to pierce the salt overhang was dry but did not explore much of the sediment volume beneath the salt overhang.

The Kotyrtas North field was opened in 1986. Oil having a density of 807–973 kg m^{-3} is produced from reservoirs that range in thickness from 5 to 123 m at depths between 1050 and 1386 m. Porosities range from 20 to 27% and permeabilities from 22 to 280 md. Total reserves are estimated at 120 million bbl. A 6- to 26-m gas cap contains 61.3% methane, less than 13.3% ethane, less than 7.8% propane, less than 6.9% nitrogen, and less than 14.6% CO_2 (Votsalevsky et al., 1993).

The Novobogatinsk field (Figure 1) is another example of first-generation hydrocarbons concentrated in the basin. Oil is trapped in a lunate lens of an onlapping Middle Triassic sequence beneath a salt sheet that extruded southward subaerially, probably at the end of the Middle Triassic and beginning of the Late Triassic (Figure 11). The diapir that extruded this 6-km-long sheet of allochthonous salt upbuilt through prekinematic Upper Permian and Lower Triassic strata during Middle Triassic deposition in a primary salt-withdrawal basin. Lower Jurassic deposition buried the extruded salt before the sheet sank into a secondary salt-withdrawal basin that migrated distally during periods of active upbuilding of the buoyant salt stock through superposed rocks. The distal 3 km of this sheet is anhydritic and has been attributed to Triassic reprecipitation of Kungurian salt (Volozh et al., 1994). However, this same phenomenon has been observed in present-day Iran and has been attributed to the partial dissolution of the early distal extrusion of younger salt (Cambrian in Iran, Kazanian in the Pricaspian) before the later extrusion an older salt (Neoproterozoic in Iran, Kungurian in the Pricaspian; Talbot and Alavi, 1996).

Low-sulfur oil (0.05–0.24 wt.% S) having a density of 632–838 kg m^{-3} from the Novobogatinsk field is produced from 11 reservoirs, which range in thickness from 40–310 m at depths between 1640 and 1900 m. Porosities range from 15 to 21.5% and permeabilities from 1 to 9 md. Total reserves are estimated at 30 million bbl. Associated gas contains less than 80.5% methane, less than 16.2% ethane, less than 8.1% propane, less than 1.9% isobutane, 1.61% nitrogen, and less than 0.2% CO_2 (Votsalevsky et al., 1993).

The Kirikli gas field near Astrakhan (Figure 1) is an example of the third generation of hydrocarbons in the basin. Shale in the infills of Early Pliocene canyons having bases at depths of 300–400 m capped methane in solution in overpressured groundwater. Reserves of about 140 tcf of gas are extracted at a rate of about 500,000 mcf gas/day, but the potential for blowouts is high.

CONCLUSIONS

The Pricaspian basin lies north of the present-day Caspian Sea and is underlain by Kungurian salt (Figure 3). The basin infill is divided into three major sedimentary sequences: subsalt strata, salt, and salt overburden (Konishev and Volozh, 1990).

The subsalt sequence contains Riphean through Lower Permian strata punctuated by unconformities. The subsalt sequence has a complex depositional history dominated by carbonate reefs and clastic fans. The salt sequence consists of Kungurian (260 Ma) salt overlain by Kazanian (255 Ma) salt to a thickness of 4.5 km in the center of the basin. The overburden of salt consists predominantly of terrigenous Upper Permian through Neogene strata. Gentle unconformities at Upper Permian–Triassic, Jurassic–Miocene, and Pliocene–Quaternary divided the overburden into three structural levels (Figure 8).

The location of 1800 structures attributed to movements of Permian salt determined structures in the overburden (Figure 6). These are distinguishable into a variety of styles representing different stages of growth, mainly as a result of two main phases of movement of the salt driven by differential loading by its overburden in a closed basin. The different sizes, shapes, and maturities of salt structures in different parts of the basin reflect areal differences in salt thickness and loading history.

Kungurian salt remains flat lying on shelves starved of clastic sediments along the north and west margins and were tilted shoreward between down-to-basin faults along the narrow slopes (zone D2, Figure 5). Offshore, in the basin center, slow and almost continuous deposition downbuilt an unusually thick salt into huge massifs. In marked contrast, the development of the Ural orogen to the east (Figure 2a) influenced the structures being downbuilt in Permian salt from the eastern and southeastern margins in Permian–Triassic times (from zones A and D1 to B, Figure 5). The early influence was by the rapid basinward progradation of sediments derived from the Urals in the east, then from the South Emba shear zone in the southeast that downbuilt salt walls, and then stocks beneath the migrating slope. Later, as their deep source layer closed to primary welds, these early salt structures became starved, and distal thrusts propagating from the Urals (Figure 2a) emphasized the margin-parallel grain of those along the eastern margin (zone A, Figure 5). Gravity alone was the dominant influence on structures developing in the salt and its overburden elsewhere in the basin.

Primary salt-withdrawal basins clearly visible in the Upper Permian–Triassic strata (Figures 5, 7, 9–11) indicate the first salt movements. Thereafter, zones of abruptly downbuilding stocks migrated basinward from the east, southeast, and southern margins of the basin in front of a widening zone of starved salt walls (Figure 2a). From Triassic to Jurassic and probably into the Cretaceous, another zone of salt structures extruding Permian salt as domes with or without overhanging allochthonous sheets separated these zones. Some extruded Permian salt may have been dissolved and redeposited as autochthonous salt beds (Volozh et al., 1989, 1999). Salt extrusion continued during a 35-m.y.-long hiatus in deposition from near the end of the Triassic to the Middle Jurassic. This extrusion starved several basin-marginal salt structures by withdrawal of salt from their deep source layer.

Subsequent deposition of shallow-water Jurassic sediments was sufficiently rapid to unconformably bury the Upper Permian–Triassic sequence deformed by salt structures, many of which had already reached the surface. Burial caused overpressuring of fluids beneath the deep Kungurian salt layer and flushed sulfurous hydrocarbons from them up through the margins of primary salt welds into the sediments surrounding starved salt structures. However, not all the deep salt supplying more basinward Permian–Triassic salt structures had been squeezed to the surface, and resumption of burial in Middle Jurassic time reactivated many still-potent salt structures.

The polygonal spoke pattern inherited from the Permian–Triassic partial gravity overturn subsequently propagated in a simpler movement pattern of Cretaceous to post-Cretaceous, polygonal, asymmetric grabens. The roots of these grabens extend to the crests of reactivating salt structures. These structures upbuilt narrow salt walls or small diameter stocks to the depositional surface which were then downbuilt in the hanging walls of normal growth faults. Terrigenous Pliocene shales in some of these grabens are known to trap sweet oil that migrated northward into the southern half of the Pricaspian basin in Cretaceous times.

Although many salt structures continued to rise, particularly near the center of the Pricaspian basin, the story of the basin changed drastically when its drainage level dropped nearly 1 km in response to the rapid Neogene opening of the Caspian basin to the south. Rapid fluvial erosion incised deep canyons into Pricaspian sediments and exposed some salt diapirs. Methane flushed from the south is trapped in the coarse Pliocene clastic infills to these canyons.

Our hope is that improved understanding of the geologic history of the Pricaspian basin and its surroundings will lead to further development of its rich hydrocarbon potential.

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