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Late Cenozoic deformation in the South Caspian region: effects of a rigid basement block within a collision zone

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Abstract

Active deformation in the South Caspian region demonstrates the enormous variation in kinematics and structural style generated where a rigid basement block lies within a collision zone. Rigid basement to the South Caspian Basin moves with a westward component relative both to stable Eurasia and Iran, and is beginning to subduct at its northern and western margins. This motion is oblique to the approximately north–south Arabia–Eurasia convergence, and causes oblique shortening to the south and northeast of the South Caspian Basin: thrusting in the Alborz and Kopet Dagh is accompanied by range-parallel strike–slip faults, which are respectively left- and right-lateral. There are also arcuate fold and thrust belts in the region, for two principal reasons. Firstly, weaker regions deform and wrap around the rigid block. This occurs at the curved transition zone between the Alborz and Talysh ranges, where thrust traces are concave towards the foreland. Secondly, a curved fold and thrust belt can link a deformation zone created by movement of the basement block to one created by the regional convergence: west-to-east thrusts in the eastern Talysh represent underthrusting of the South Caspian basement, but pass via an arcuate fan of fold trains into SSW-directed thrusts in the eastern Greater Caucasus, which accommodates part of the Arabia–Eurasia convergence. Each part of the South Caspian region contains one or more detachment levels, which vary dependent on the pre-Pliocene geology. Buckle folds in the South Caspian Basin are detached from older rocks on thick mid-Tertiary mudrocks, whereas thrust sheets in the eastern Greater Caucasus detach on Mesozoic horizons. In the future, the South Caspian basement may be largely eliminated by subduction, leading to a situation similar to Archaean greenstone belts of interthrust mafic and sedimentary slices surrounded by the roots of mountain ranges constructed from continental crust.

Keywords: Arabia–Eurasia collision; Buckle fold; Thrust; South Caspian Basin; Subduction

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1. Introduction

This paper describes the young and active structural styles in the fold and thrust belts of the South Caspian region, which lies at the northern side of the active Arabia–Eurasia collision zone (Fig. 1). The westward motion of the rigid South Caspian basement is very different to the roughly north–south plate convergence between Arabia and Eurasia, and this produces kinematics in the fold and thrust belts that surround the South Caspian Basin that are not predictable from the overall convergence. We show that this kinematic variation is distinct from the exact structural style in each area, which is strongly dependent on the pre–late Cenozoic crustal structure and stratigraphy.

It is disputed when the Arabia–Eurasia collision began. Estimates include 12 Ma (Dewey et al., 1986), or much earlier in the Tertiary (~ 40 Ma; Hempton, 1987). The youngest estimate still significantly predates the onset of folding in the South Caspian Basin, which began at 3–5 Ma (Aliev, 1960; Devlin et al., 1999), at roughly the time of the start of rapid exhumation in the Alborz mountains to the south (Axen et al., 2001).

A key feature of the Arabia–Eurasia collision is the presence of trapped blocks of rigid crust within the Eurasian continent, surrounded by active fold and thrust belts (Dewey et al., 1986; Jackson and McKenzie, 1988; Kopp, 1997). These rigid blocks underlie the thick sedimentary cover of the Western and Eastern Black Sea basins and the South Caspian Basin (Shikalibeily and Grigoriants, 1980; Robinson et al., 1996). All three basins are relatively aseismic, showing the strength and rigidity of their basement compared with adjacent areas. The properties of seismic waves passing through the South Caspian Basin are consistent with a basement of either unusually thick oceanic crust, or thinned, high velocity continental crust (Mangino and Priestley, 1998). Left-lateral and right-lateral active faults in the Alborz and Kopet Dagh respectively show that the South Caspian has a westward component of motion relative to stable Eurasia to its north and Iran to its south (Fig. 2; Priestley et al., 1994; Jackson et al., 2002). Revising the velocity triangle of Jackson et al. (2002) with the Arabia–Eurasia plate motion of Sella et al. (2002), who calculated overall convergence to be ~ 10 mm/year slower than the NUVEL-1A estimate of DeMets et al. (1994), suggests that the South Caspian converges with Iran at ~ 9 mm/year across the Alborz in the direction roughly 210°, and converges with Eurasia at ~ 5 mm/year in a direction somewhat north of 300°.

New data in this paper come from original fieldwork in the South Caspian region, specifically the Greater Caucasus, Kura Basin and Talysh regions of Azerbaijan. These observations are used with existing literature, geological maps (1:50,000 to 1:250,000 scales), satellite images and aerial photographs of key areas. We describe the geology of the Alborz and Kopet Dagh ranges more briefly. Crucially, recent GPS and seismicity studies (McClusky et al., 2000; Jackson et al., 2002) provide a kinematic framework for interpreting the exposed structures and extrapolating them to deeper levels. The rest of this paper is set out as follows: the South Caspian and Kura basins and surrounding ranges are described in turn, focusing on the style of late Cenozoic deformation. The data show that a rigid block within a collision zone can produce great variations in the kinematics of the surrounding deformation zones. The exact structural style in each area depends on other variables besides the convergence vector, such as the location of detachment zones within the crust.

2. South Caspian and Kura basins

The basement to the South Caspian Basin is nowhere exposed, being covered by a ~ 20 km thick sedimentary fill. Lack of reliable correlations between the lower part of this fill and exposed (or drilled) counterparts means that its age and original tectonic setting are in dispute. Some authors view it as a trapped relict of the Palaeo-Tethys ocean (Nadirov et al., 1997), but a more accepted scenario is that it opened as a back-arc basin north of a Neo-Tethyan arc (e.g. Brunet et al., 2003).

The northern boundary of the South Caspian Basin lies along the Apsheron Sill, which at shallow levels is a line of anticlines linking the Apsheron and Cheleken peninsulas. Its other boundaries are less precisely defined. The southern margin lies somewhere north of and parallel to the Caspian Sea shoreline on the Iranian coast. Mangino and Priestley (1998) described

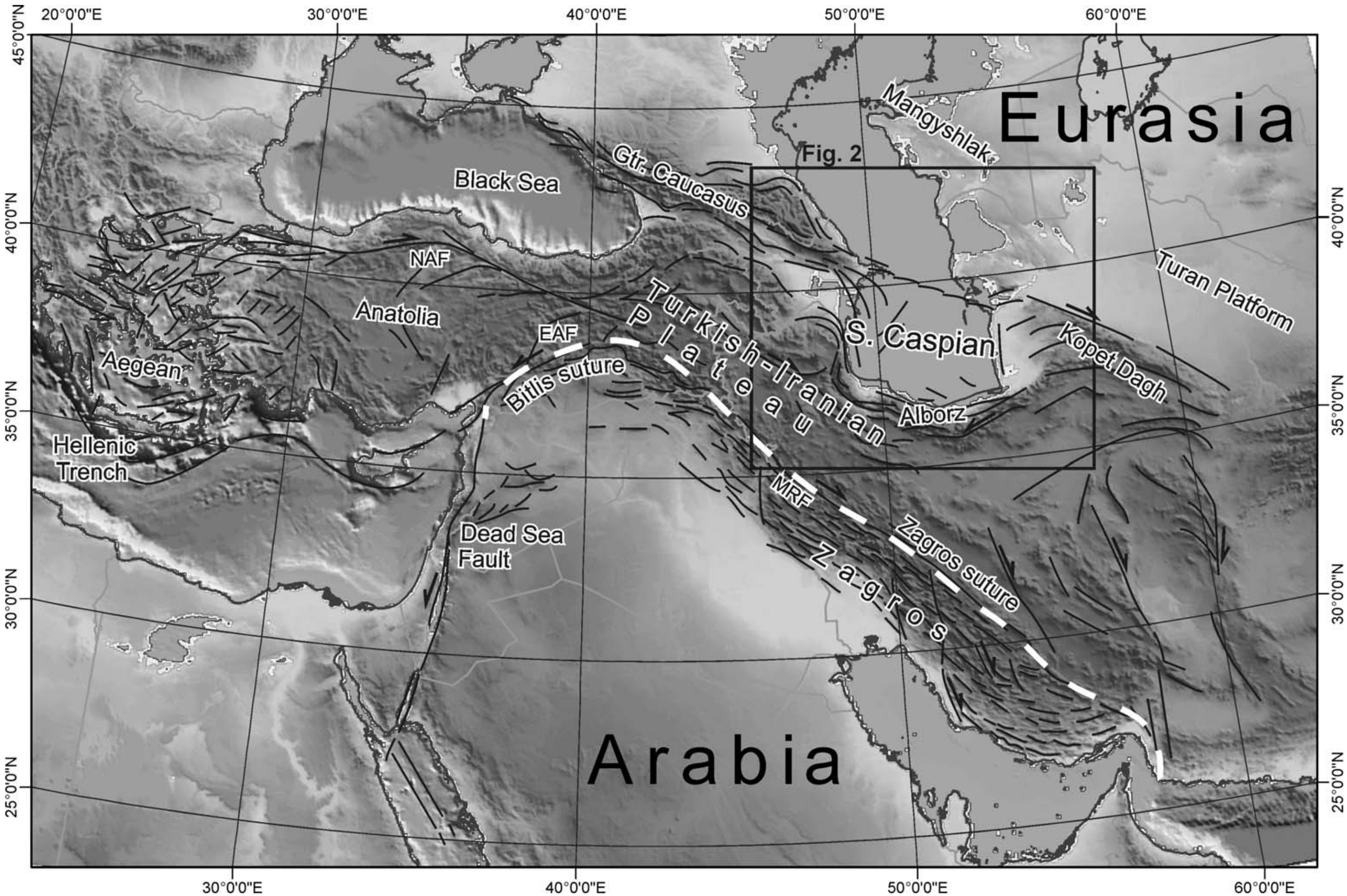


Fig. 1. Topography and regional structure of the Arabia–Eurasia collision. Principal fault zones and fold trends are highlighted. Elevated regions are principally between the Zagros and the northern side of the Greater Caucasus–Kopet Dagh range. The Arabia–Eurasia convergence has been largely accommodated by crustal shortening in the area between these range fronts. EAF = East Anatolian Fault; MRF = Main Recent Fault; NAF = North Anatolian Fault.

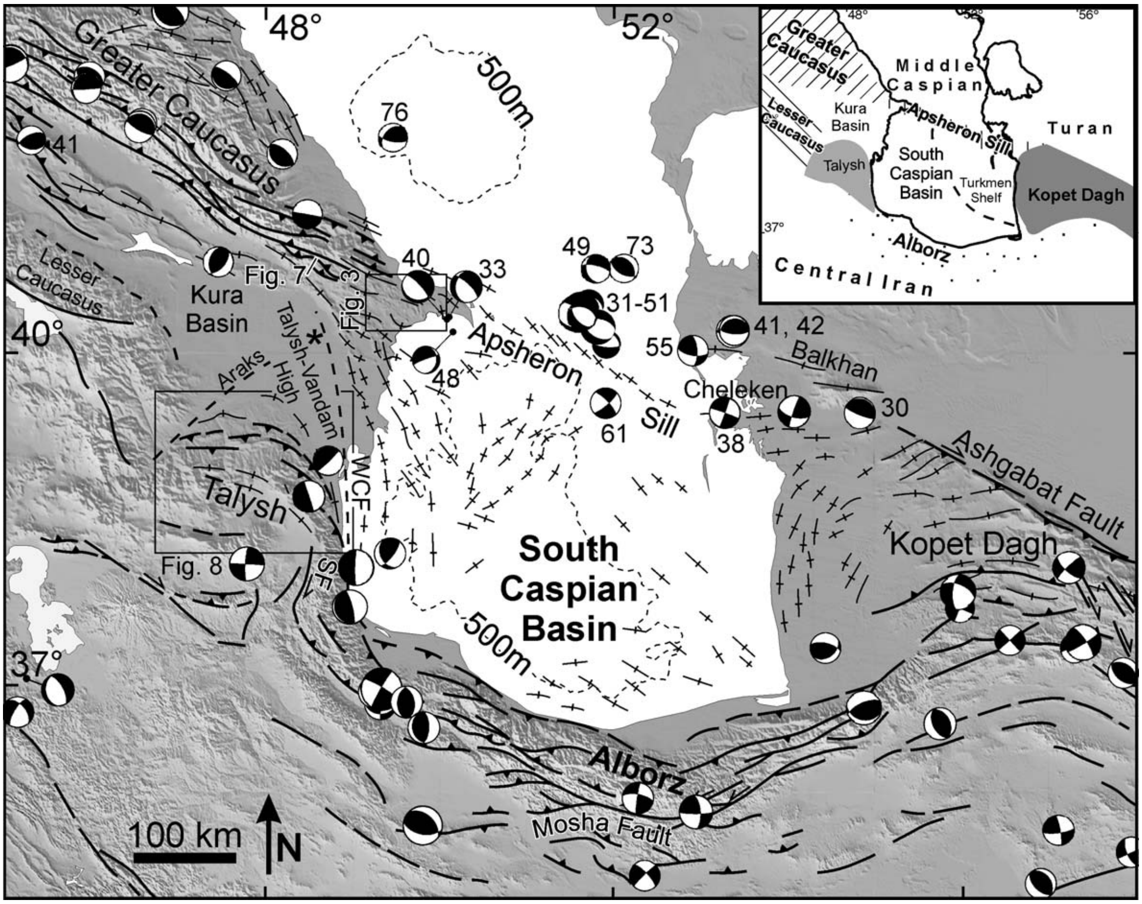


Fig. 2. Structure and seismicity of the South Caspian region. Modified after Jackson et al. (2002). Centroid depths are only shown for earthquakes deeper than 30 km. SF = Sangevar Fault; WCF = West Caspian Fault. The asterisk marks the position of the Saatly superdeep well.

the eastern and western boundaries to the high velocity basement at roughly the position of the present Caspian shorelines. The onshore Talysh–Vandam gravity high also trends north–south, parallel to and west of the western shoreline, before swinging inland into the intermontane Kura Basin (e.g. Kadirov and Askerhanova, 1998). This gravity high has been interpreted as the region west of a basement fault, named the West Caspian Fault by Khain et al. (1966). However, while these authors continued the fault northwards across the eastern Greater Caucasus, it does not affect exposed strata or other structures in this region, and so is unlikely to continue this far north.

Seismicity at the margins of the South Caspian Basin shows that it is in the early stages of subducting under the Apsheron Sill to its north, where earthquakes occur at depths of up to ~80 km, and probably also under the Talysh to its west, where gently west-dipping thrusts have depths of 15–27 km (Fig. 2; Priestley et al., 1994; Jackson et al., 2002).

The Kura Basin lies between the Lesser and Greater Caucasus (Fig. 2), and is presently the foreland basin to the fold and thrust belts within both ranges. Its pre-Pliocene history is not well known, and its boundary with the South Caspian Basin is poorly defined.

2.1. Stratigraphy

The oldest strata which are clearly identified across the South Caspian Basin are Oligo-Miocene deposits of the Maykop Suite. These are mud-prone sediments that lie at depths of 10–12 km within the basin interior. They are brought to the surface via mud volcanoes, which are associated with anticlines (Yakubov and Alizade, 1971). The Maykop Suite forms the principal hydrocarbon source rock of the basin (Abrams and Narimanov, 1997). Younger strata record a broadly shallowing upward trend in the basin, which led to the late Miocene deposition of evaporites. Fluvial–deltaic deposition of the Productive Series and its lateral equivalents took place between the latest Miocene and the early Pliocene (Reynolds et al., 1998). The Productive Series is up to 5–7 km thick in the basin interior and forms the main hydrocarbon reservoir interval in the basin. Allen et al. (2002) suggested that the marked acceleration of tectonic subsidence at ~5.5 Ma was caused by the onset of basement subduction.

A brief marine transgression in the late Pliocene led to the deposition of mudrocks of the Akchagyl Suite. This is typically the first unit in offshore folds to show thinning onto fold crests, marking the initiation of these structures (Devlin et al., 1999), but pinchouts are present in Productive Series strata onshore (Aliev, 1960), indicating that deformation may have begun slightly earlier. Pleistocene sedimentation has been non-marine and rapid, but at least in the northern part of the basin has continued to be predominantly fine-grained.

2.2. Structure

Individual folds are domal anticlines, which are imaged on offshore exploration seismic lines as buckle folds that detach within the Maykop Suite (Devlin et al., 1999). Fold orientations vary markedly across the

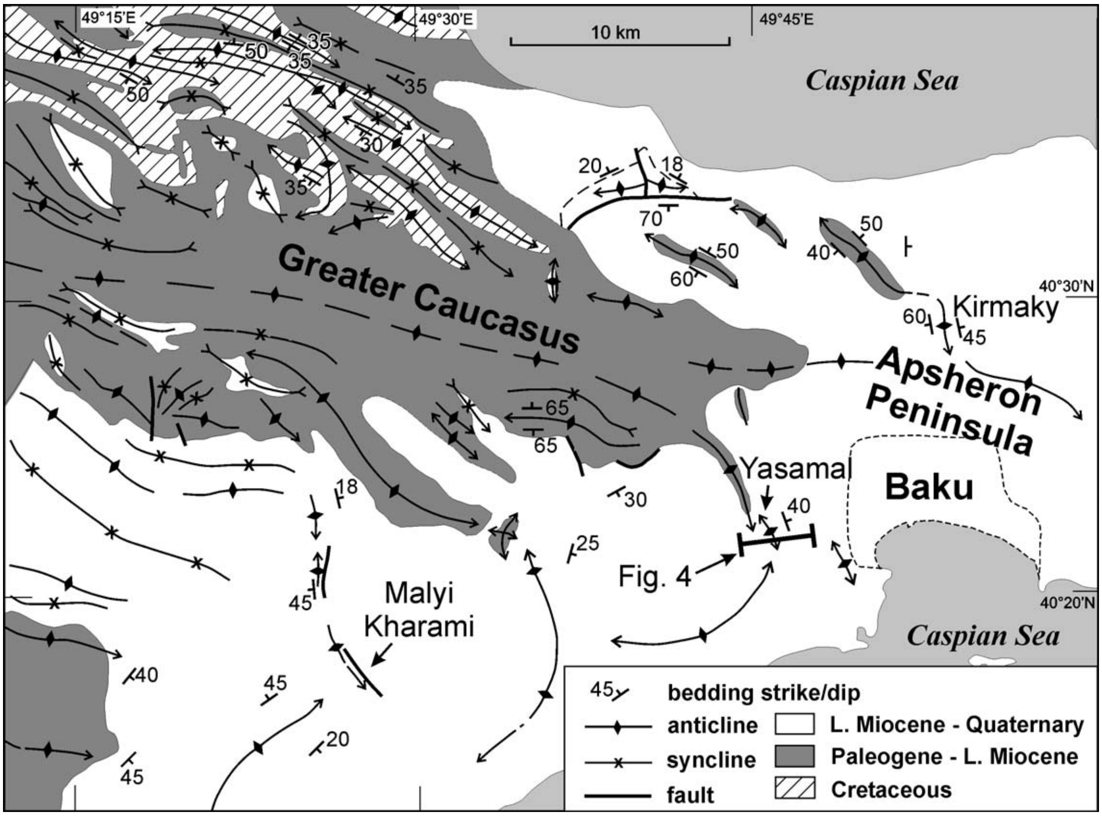


Fig. 3. Geology of the eastern Greater Caucasus and the western portion of the Apsheron Peninsula. From the Ministry of Geology and Mineral Resources, USSR (1960). Location is shown in Fig. 2.

basin. In the northwest, several fold trains fan out eastwards from the southern side of the Greater Caucasus (Fig. 2). We studied several onshore folds to examine the fold style and the geometries of associated faults, particularly Kirmaky, Yasamal (also known as Shubani) and Malyi Kharami (Fig. 3). Detailed observations on the fault zones will be presented elsewhere.

The folds in the Apsheron Peninsula are at the junction of the South Caspian Basin and the Greater Caucasus: the stratigraphy and fold style are similar to the South Caspian Basin, but the region lies along strike from the Greater Caucasus (Fig. 3). Anticlines in the Apsheron Peninsula show a marked variation in strike across the region, and individual folds commonly have curved axial traces (Ministry of Geology and Mineral Resources, USSR, 1960). This is in contrast to the linear folds further west in the Greater Caucasus (Figs. 2 and 3). The curved axial traces are associated with areas of lower exhumation, where mud volcanoes are abundant and Productive Series and younger strata are of thicknesses comparable to the South Caspian Basin offshore. Individual folds show the upright, doubly plunging form of offshore structures, and are similarly disrupted by combinations of thrust, strike–slip and extensional faults which help accommodate the strain during folding (Fig. 4). Curved axial traces may reflect strong variations in the displacement of underlying thrusts along their strike (Alsop and Holdsworth, 2002). This

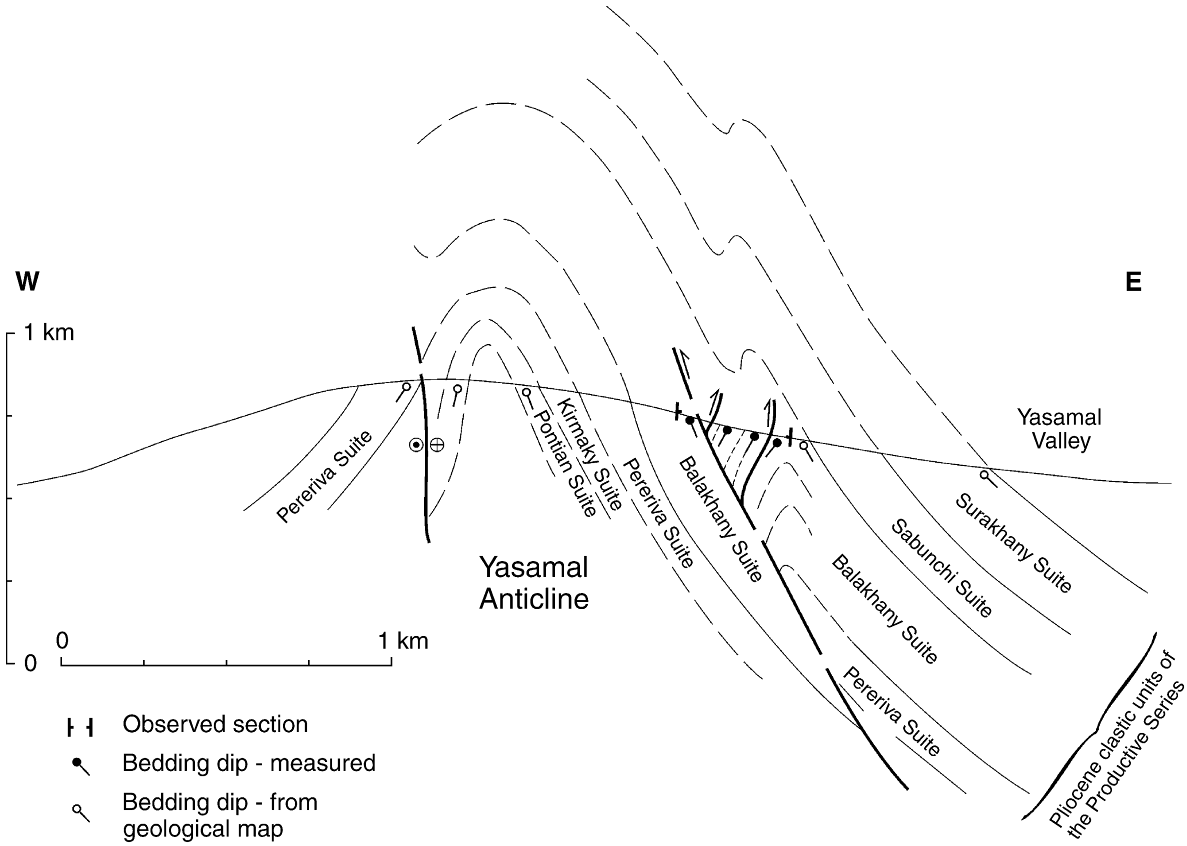


Fig. 4. Interpreted section through the Yasamal Anticline, including the thrusts on the east limb of the fold. West-dipping thrusts within the hangingwall of the main thrust suggest that overall the fault system could be a flower structure, but the small number of fault striae observed all indicate dip slip motion. The Pontian Suite is latest Miocene; the Kirmaky to Surakhany suites are units of the largely lower Pliocene Productive Series. Location is shown in Fig. 3.

behaviour could be enhanced by the mud-prone nature of the Maykop Suite, which would favour a zone of strongly ductile detachment rather than a discrete décollement plane. These exposed structures are especially valuable as analogues for sub-surface hydrocarbon accumulations (Figs. 5a and b): they expose the Pliocene reservoir stratigraphy, locally oil-charged, in the same type of structures as the oil fields.

The southwestern offshore fold train in the South Caspian Basin (Fig. 2) trends parallel to and close to the curved margin of the Talysh–Vandam gravity high. Individual folds in this train are aligned in a slight right-lateral en echelon array, indicative of right-lateral transpressional deformation. Trifonov (1978) depicted fold parallel right-lateral faulting in this region, but we cannot confirm this. The anticlines are associated with abundant mud volcanoes, which typically lie on the hinge lines of the anticlines, but not necessarily at their culminations at present exposure levels (Fig. 5c). West and southwest of this fold train there are no high amplitude folds within the late Cenozoic cover of the Kura Basin and no mud volcanoes. The Kura River is deflected $\sim$ 50 km southwards before it reaches the

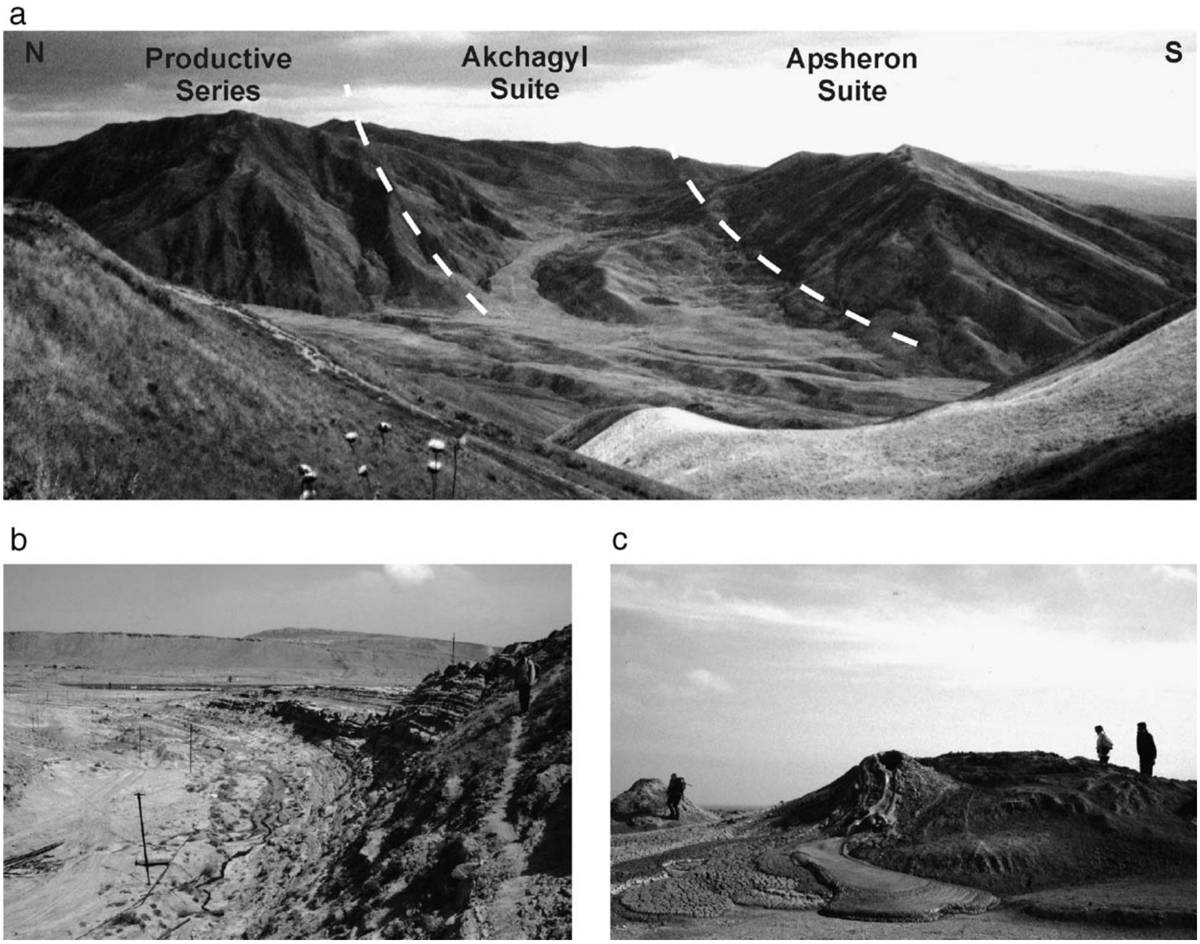


Fig. 5. (a) View east of folded Plio-Quaternary strata at the southeastern side of the Greater Caucasus, at 40°27.25′N 48°40.56′E. Progressive decreases in the dip of Akchagyl and Apsheron strata may indicate deposition during the growth of this fold, similar to the pinchouts seen in sub-surface data. (b) Folded Plio-Quaternary strata at the southern end of the Yasamal Anticline, looking east. Fluvial–deltaic clastics of the Productive Series are in the foreground; the ridge-forming unit on the skyline is a folded sandy limestone from the Pleistocene Apsheron Suite. (c) Typical mud volcano cones at the margin of the Caspian Sea.

Caspian Sea (Fig. 6). This is not the result of offset along a discrete fault, but instead represents the re-organization and re-channelling of the river as it attempts to keep flowing into the South Caspian Basin through the rising folds.

There is a major difference in stratigraphy between the Talysh–Vandam high and the folds to its northeast. On the high, the Saatly deep well penetrated a total of about 3 km of Cenozoic clastics, overlying ~ 5 km of drilled Jurassic and Cretaceous andesitic volcanics and clastics (Nadirov et al., 1997). East of the high, the Productive Series alone reaches thicknesses of over 3 km on onshore oil fields of the Kura Basin, while the presence of mud volcanoes and Maykop-sourced oil in the same region shows that the Maykop Suite has a significant thickness (Inan et al., 1997). While uncertain, the total Cenozoic sedimentary thickness between the modern Kura River and the Greater Caucasus must be much greater than over the Talysh–Vandam high.

To summarise, several north–south trending features are coincident along the line of the West Caspian Fault proposed by Khain et al. (1966), namely: the eastern edge of the Talysh–Vandam gravity high, the western margin of north–south folds in the Kura Basin, the western limit of mud volcanoes, the approximate change between thick and thin Tertiary strata and the western limit of the thin, high velocity basement of the South Caspian Basin.

The western line of folds in the South Caspian and Kura basins changes in orientation northwards, from north–south to WNW–ESE (Fig. 2). This matches the change in slip vector of the thrust earthquakes in the Talysh and eastern Greater Caucasus (Priestley et al., 1994; Jackson et al., 2002). There need not be a direct physical connection between the thrusts at

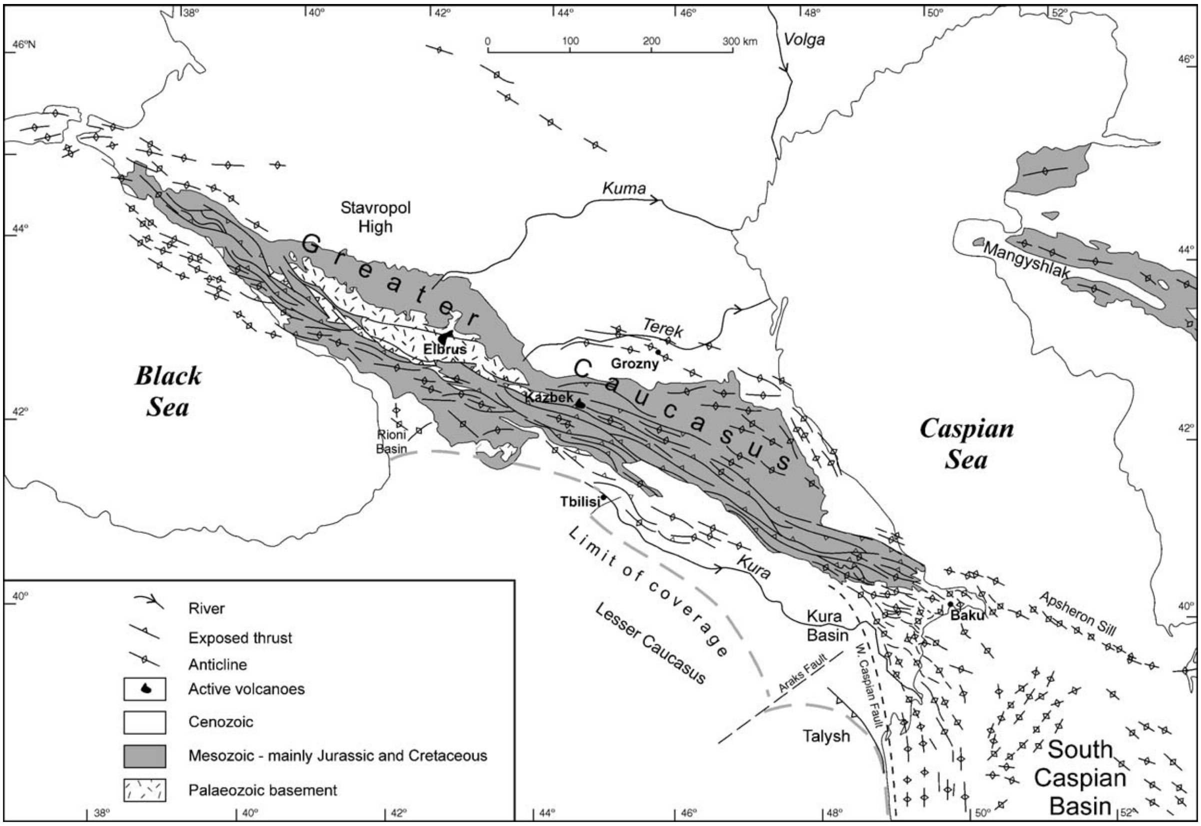


Fig. 6. Structure of the Greater Caucasus and adjacent regions. Compiled from several sources, principally Nalivkin (1983) and Yakubov and Alizade (1971).

depth and the exposed folds, because the Maykop Suite provides a likely detachment level between the two.

3. Greater Caucasus

The Greater Caucasus range lies north of both the Black Sea and the South Caspian Basin (Fig. 6). Palaeozoic basement exposed in the core of the range has a poorly known history. Thick Lower Jurassic marine clastics and intercalated MORB-like tholeiitic sills have been interpreted as recording major extension in a Neo-Tethyan back-arc basin (Sengör, 1984). The links of this basin to the South Caspian region at this time are uncertain. Younger Mesozoic strata in the Greater Caucasus consist of fringing carbonate and clastic buildups north and south of a central trough, which continued to accumulate deepwater marine clastics (Zonenshain et al., 1990). Outliers of mid Tertiary marine clastics in the eastern Greater Caucasus show that at least this part of the range underwent deposition well into the Tertiary.

The present structure of the Greater Caucasus exposes its Palaeozoic basement in dominantly southward-directed thrust slices, but only west of ~44°E (Fig. 6). The Jurassic and Cretaceous strata are present in tight or isoclinal folds across the range around the exposed Palaeozoic core (Kopp and Shcherba, 1985; Dotduyev, 1986; Sholpo, 1993). These are associated with thrusts. The vergence of the folds is predominantly towards the south, and the greatest throw on individual thrusts occurs on the southern side of the range, also towards the south. Plio-Quaternary strata are folded into elongate, linear, south-vergent anticlines on the southern side of the range, between the extant Kura and Rioni basins. However, there are north-directed structures on the northern margin, especially in the northeast (Sobornov, 1994). The Moho under the range is at depths of up to 60 km (Ruppel and McNutt, 1990).

GPS surveys across both the Greater and Lesser Caucasus provided a minimum north–south shortening rate of 10 ± 2 mm/year (Reilinger et al., 1997), of which ~60% is estimated to occur across the Greater Caucasus (McClusky et al., 2000). This contrasts with previous estimates for the Greater Caucasus based on seismicity data of 1.3 mm/year (Philip et al., 1989), 3.4 mm/year (Jackson, 1992) and 2–6 mm/year (Westaway, 1990).

The timing of initial Cenozoic compression across the Greater Caucasus is controversial. Different studies in different parts of the range and its forelands imply initial ages ranging from the late Eocene in northern Georgia (Banks et al., 1997) to late middle Miocene in Dagestan (Sobornov, 1994). Over time, compressional deformation has probably propagated towards the foreland basins to the north and south of the range, and also laterally towards the northern side of the South Caspian Basin. Evidence for this is the incorporation of latest Miocene shallow marine strata into folds at the eastern side of the Greater Caucasus (Azizbekov, 1972).

Fig. 7 is a cross-section through part of the eastern Greater Caucasus at Lagich, based on our fieldwork in this area. The section shows Cretaceous and Maykop Suite strata in thrust-bound, overturned, south-vergent synclines. The Maykop Suite consists predominantly of organic-rich mudrocks, similar to equivalent strata in the South Caspian Basin. The Cretaceous is lithogically variable, including carbonates, basic-andesitic volcanics and rhythmic sandstone–mudstone couplets, which we interpret as turbidites. Clastics become predominant over carbonates northwards. Each of the tight synclines contains internal deformation, principally by bedding-parallel shear. Pencil structures and slaty cleavage are locally developed, but the strata are not strongly metamorphosed. Several features are distinctive about the structure in this section. There are synclines separated by thrusts, with no intervening anticlines; there are footwall cutoffs of steeply dipping bedding by gentler-dipping thrusts; one fault contact places younger over older strata (Maykop over Cretaceous), albeit with minor folds which indicate top-to-south displacement of the Maykop. To explain these features, we suggest that there was sufficient thrusting along the lower limbs of overturned synclines to juxtapose them at the present exposure level. Existing geological maps show several klippen in this region (Khain et al., 1966), and interpret a thin-skinned style of deformation similar to Fig. 7. This implies that there are one or more décollement horizons within the Mesozoic succession.

Fold patterns in the eastern Greater Caucasus (Fig. 3) include regions of distinctive dome-and-basin geo-

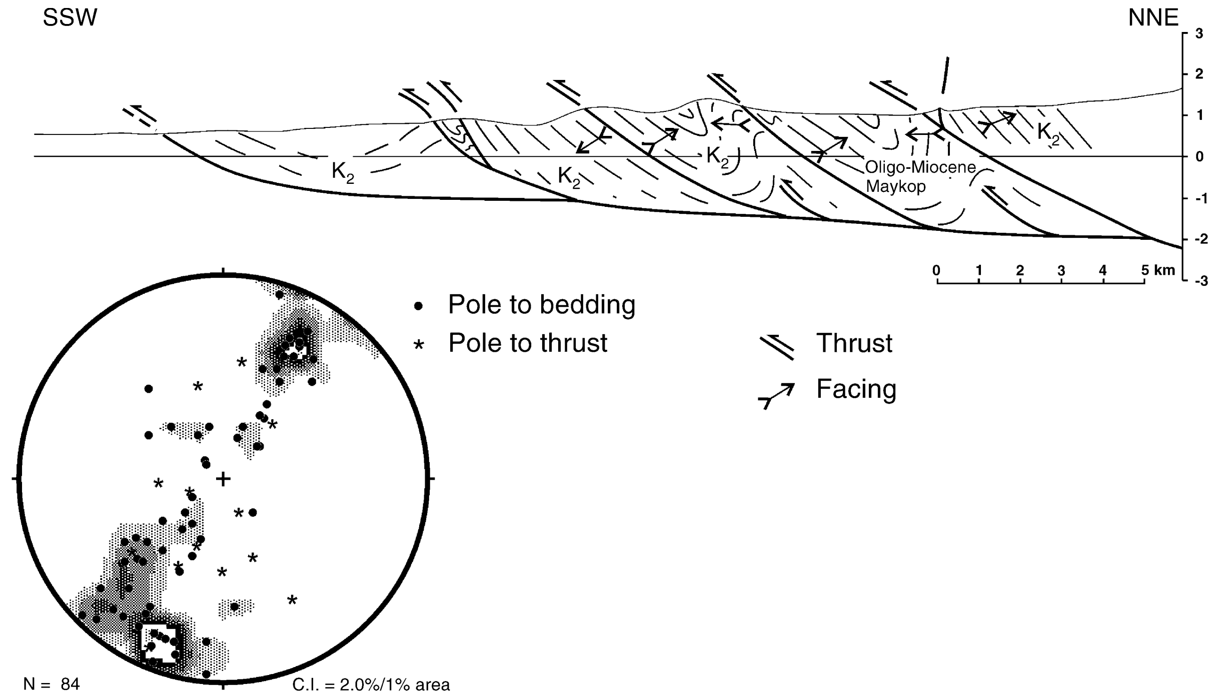


Fig. 7. Interpreted structure of the Lagich cross-section, Azerbaijan Greater Caucasus. Location is shown in Fig. 2.

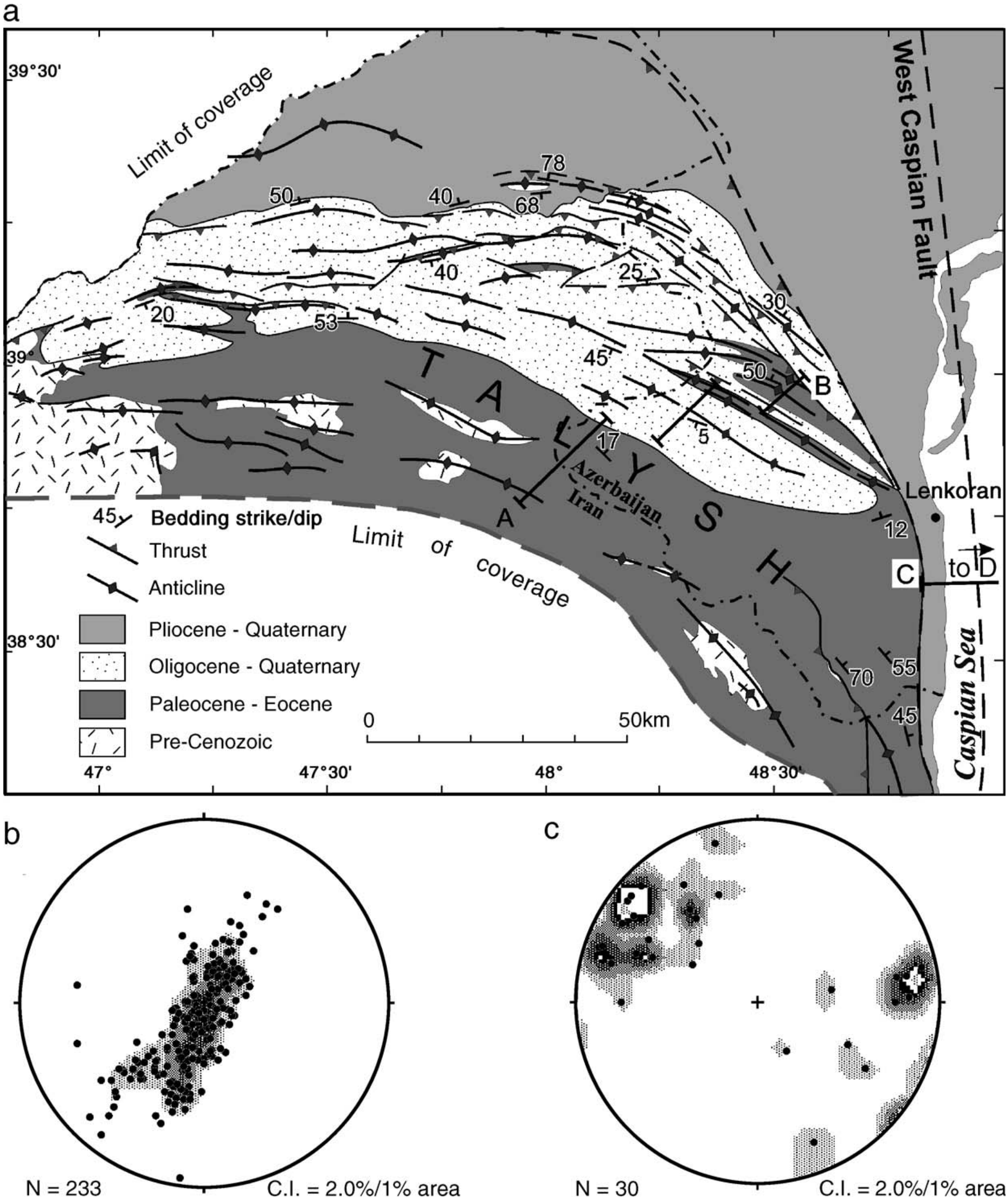
metries, defined by the low aspect ratios of both anticlines and synclines (see Allen et al., 2001 for a review). The origin of these features is enigmatic. Refolding seems unlikely, given that we observe no structural overprinting at outcrop scale or in regional map patterns. Refolding would imply rapid and major switching of stress axes in the last few million years, for which there is no evidence. An alternative possibility is constrictional deformation, noted for producing dome-and-basin fold patterns (Ghosh et al., 1995). Constrictional deformation is typical where compressional stresses of different orientations and origins act at the same time on a region. Assuming the eastern Greater Caucasus is affected by both the westward motion of the South Caspian basement and shortening induced by the Arabia–Eurasia convergence, then it may be a region of gross constrictional deformation.

4. Talysh

The Talysh (Talesh) mountains lie to the southwest of the South Caspian Basin, east of the Lesser Caucasus and west of the Alborz (Figs. 2 and 8). The range is in both Azerbaijan and Iran, and the description in this section is taken from our fieldwork in the Azerbaijan Talysh combined with large scale (1:200,000 and 1:250,000) geological maps from both countries (e.g. Ministry of Geology and Mineral Resources, USSR, 1957; Geological Survey of Iran, 1994). Data from these maps are collated in Fig. 8, with input from our own fieldwork.

Little has been published in the international literature on the stratigraphy or pre–late Cenozoic evolution of the Talysh. Mesozoic strata exposed in northwest Iran and the extreme south of the Azerbai-

Fig. 8. (a) Geology of the Talysh region. Compiled from the Ministry of Geology, and Mineral Resources, USSR (1957, 1958) and Geological Survey of Iran (1987, 1994), with information from our fieldwork in the Azerbaijan Talysh. (b) Stereoplot of poles to bedding planes measured along transect A–B in (a). Contoured data are also shown. The average strike of the bedding planes is 299°, this is oblique to the topographic fronts along the eastern side of the range. See text for discussion. (c) Stereoplot of fold hinge lines measured along transect A–B in (a). Contoured data are also shown. The data show a predominance of fold hinges plunging gently to the west–northwest or northwest. See text for discussion.


a
39°30'
39°
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47°
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Limit of coverage
West Caspian Fault
78
50
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40
25
30
20
53
45
50
B
17
5
Azerbaijan
Iran
A
T A L Y S H
Lenkoran
12
C
to D
70
55
45
Caspian Sea
45 Bedding strike/dip
Thrust
Anticline
Pliocene - Quaternary
Oligocene - Quaternary
Paleocene - Eocene
Pre-Cenozoic
0
50km
b
N = 233
C.I. = 2.0%/1% area
c
N = 30
C.I. = 2.0%/1% area

jan Talysh appear to be similar to the mixed clastic carbonate succession of the Alborz to the east; the extensive Mesozoic volcanics of the Lesser Caucasus and the Saatly deep well in the Kura Basin (Nadirov et al., 1997) are not present. Paleocene–Eocene volcanics are high-K basalts, similar in composition to rocks of similar age in the Achara–Trialet belt of Georgia and the Pontides of northern Turkey (Kazmin et al., 1986). They are intercalated with clastic turbidites of volcanic provenance, and the combined volcanic and sedimentary succession is at least 7 km thick. Palaeocurrents are directed towards the South Caspian Basin to the east and southeast (unpublished CASP/GIA data). Overlying Oligocene turbidites lack volcanic intercalations and are correlated with the regional Maykop Suite (Azeri Petroleum Expedition, 1958). Although published geological maps of Azerbaijan show a pronounced angular unconformity at the base of the Oligocene strata (Ministry of Geology and Mineral Resources, USSR, 1957, 1958), we found no evidence of this in the field. Nor is it depicted on the Iranian maps (Geological Survey of Iran, 1987, 1994).

The Talysh is an arcuate fold and thrust belt (Fig. 8); structures swing in strike from north–south in the east to ENE in the west. Exposed rocks are predominantly Paleogene volcanics and sediments, although Mesozoic strata are exposed in anticlines in the interior of the range within Iran, and Miocene and Pliocene clastics are exhumed in the external parts of the range. Folds and thrusts verge towards the external parts of the range, while fold wavelength decreases in this direction.

The western boundary to the Talysh is along the Araks River, which has been suggested as the position of a fault zone, the Araks Fault (Fig. 2; e.g. Jackson and McKenzie, 1984). Fault rocks are not exposed, and the seismicity data for the presumed line of the fault are ambiguous (Jackson et al., 2002). Nevertheless, this line separates the Tertiary strata of the Talysh from Mesozoic volcanics, metamorphic rocks and ophiolites of the Lesser Caucasus (Adamia et al., 1981). Although the Lesser Caucasus has undergone late Cenozoic crustal shortening, it is not clear how much active deformation there is at the present time: the range front lacks the major thrust events associated with the Talysh (Fig. 2), and the Lesser Caucasus contains Quaternary basaltic lava fields and extensional faults, which the Talysh does not (Rebai et al., 1993; Kocyigit et al., 2001).

In the interpreted cross-section through the Azerbaijan sector of the Talysh (Fig. 9), shallow-level

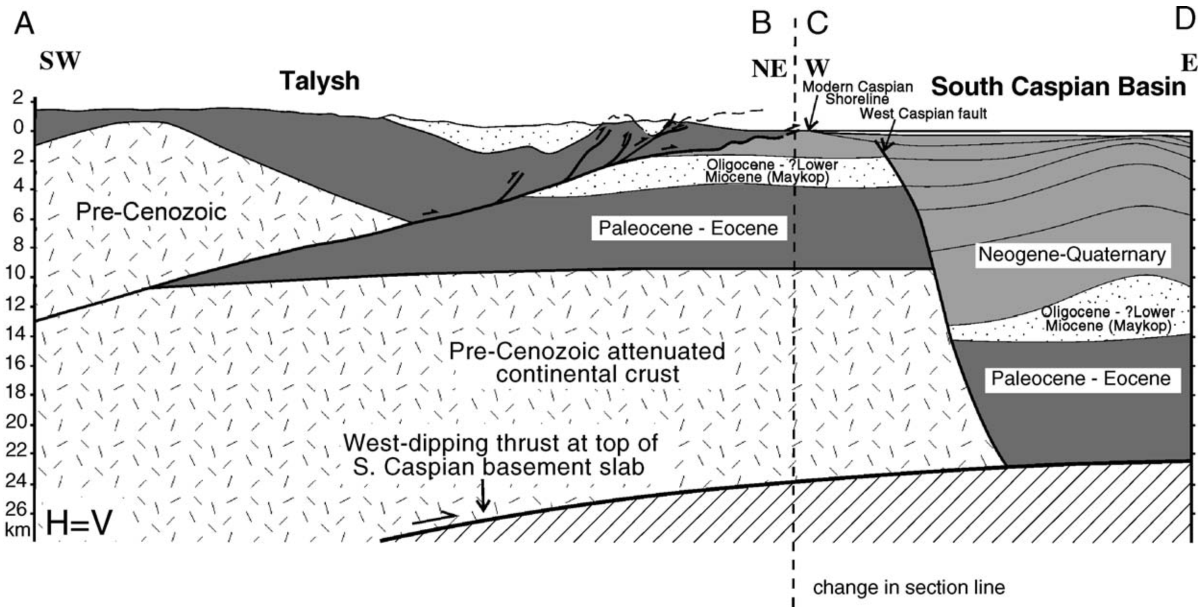

Fig. 9. Interpreted cross-section through the eastern Talysh. See text for discussion. Location is shown in Fig. 8.

thrusts are shown as splaying off a main thrust which dips towards the interior of the range, and carries the entire Mesozoic–Tertiary stratigraphy in its hangingwall. There is abundant minor deformation within the Maykop Suite, but it does not act as a major, regional décollement zone. This is not surprising, given that the Maykop strata are typically not as mud-prone as their equivalents to the north.

Two thrusts at the eastern side of the Talysh are associated with sharp breaks in the topography. We did not observe such a relationship in any structures further west, nor do the topographic breaks appear to be linked to any changes in bedrock lithology across the faults (Figs. 2 and 8a). These two thrusts also strike clockwise of the measured structures to their west (Figs. 8b and c), and cross-cut these fold and fault trends. Together, these exposed thrusts and the seismogenic thrusts at depth (Jackson et al., 2002) suggest that active deformation in the Talysh is concentrated along the eastern side of the range, and involves overthrusting of the South Caspian Basin to the east.

The offshore part of the section line in Fig. 9 is more schematic, but based on published data for the thickness and deformation style of the Cenozoic succession in the South Caspian Basin (e.g. Devlin et al., 1999; Inan et al., 1997). In particular, the nature and geometry of the South Caspian Fault is highly speculative; it is even uncertain whether it has an extensional component and dips east, as shown, or is a thrust which dips steeply towards the Talysh. Whatever its nature, there is major structural relief between the interior of the Talysh where the Maykop Suite is exposed, and the interior of the South Caspian Basin, where it is typically buried at 10–12 km (e.g. Abrams and Narimanov, 1997).

5. Alborz

The Alborz range, northern Iran, is a chain of mountains along the southern side of the Caspian Sea (Figs. 1 and 2). It is roughly 600 km long and 100 km across, with several summits >4000 m in altitude. The range is tectonically active, and the seismicity record shows both range-parallel left-lateral and thrust faulting (Berberian, 1997; Berberian and Yeats, 1999; Jackson et al., 2002). A more detailed account of the structure of the Alborz is presented elsewhere, based on original fieldwork in the range (Allen et al., 2003). In summary, roughly north–south shortening occurs on thrusts which dip inwards from the range margins (e.g. Geological Survey of Iran, 1991). Several thrusts have throws of $\sim$ 8–10 km. Precambrian metamorphic basement is not exposed, because of detachment along upper Proterozoic evaporites and the great thickness of the deformed sedimentary succession ($\sim$ 10 km). Other detachment levels occur within Lower Jurassic mudrocks and coal measures, Upper Cretaceous marls and Tertiary evaporites. Exposed thrusts are variously ramps or flats within the cover, or isolated klippen.

Active left-lateral strike–slip faults trend ENE in the east of the range, WNW in the west. Unlike thrusts, seismogenic strike–slip faults produce prominent surface ruptures. Restoration of a truncated anticline shows that the eastern Mosha Fault has a left-lateral offset of $\sim$ 30–35 km, while total shortening across the range is $\sim$ 30 km (25–30%) at the longitude of Tehran ($\sim$ 51°30′E) (Berberian, 1983; Allen et al., 2003). Cenozoic right-lateral slip took place on WNW-trending faults between 50° and 52°E, but this deformation does not appear to be active (Axen et al., 2001).

At the western margin of the Alborz, thrusts which transport broadly to the southwest change in strike to merge with the NNE-trending, right-lateral Sangavar Fault (Berberian and Yeats, 1999) and several subparallel, linear structures to its east, which we infer to be other right-lateral faults. Segments of the Sangavar Fault may have ruptured in 1863 and 1896. It has the orientation and sense of motion to allow northward motion of the interior of the Talysh relative to the Alborz and the South Caspian (Fig. 2).

Although the structure of the Alborz in cross-section is roughly symmetrical, the erosion level is not. Thick ($\sim$ 5 km) successions of Eocene turbidites and interbedded volcanics crop out extensively on the southern side of the range, but not on the northern side (Alavi, 1996; Allen et al., 2003). This may reflect the original distribution of these rocks, perhaps within a narrow rift basin separate from the South Caspian Basin to the north (Brunet et al., 2003). However, the considerable late Cenozoic exhumation on the northern side of the Alborz ($\sim$ 5–7 km since 7 Ma in one area; Axen et al., 2001) may mean that a thick early

Tertiary succession has been removed from this region. A major control on relative erosion and exhumation rates may be the much higher precipitation on the northern side of the range, which reaches 2000 mm/year, compared with only 200–400 mm/year on the southern side (Allen et al., 2003).

6. Kopet Dagh

The Kopet Dagh range trends at 120–300° for 700 km through northeast Iran and Turkmenistan between the Caspian Sea and the Afghanistan border (Figs. 1 and 2). It separates the Turan platform from central Iran. The range is up to 3000 m in altitude, some, 2000 m higher than the Turkmen foreland to the north. Jurassic–Miocene marine carbonates and clastics were deposited across a region now deformed into a series of folds and thrusts. These are broadly convex northwards, and curve into the trend of the range-parallel, right-lateral Ashgabat Fault at the northern margin of the range (Trifonov, 1978). This fault also has a component of thrust motion to the north (Priestley et al., 1994). Relief in the range dies out westwards, towards the eastern margin of the South Caspian Basin. Folds at the Caspian shoreline strike north–south, indicating a component of east–west shortening, although there are no focal mechanisms for this area (Fig. 2).

At the western end of the range, west of 56°E, altitudes are lower, and the Ashgabat Fault passes into two lines of isolated folds in the Balkhan region. These have a more east–west trend than either the Ashgabat Fault or the folds within the Apsheron Sill, further west. The southern set of folds passes into the eastern part of the Apsheron Sill. Focal mechanisms in this area show north-to-south overthrusting on gently north-dipping planes (Jackson et al., 2002). These events are relatively deep (~ 30–40 km). In map view, fold and fault trends between the western end of the Ashgabat Fault and the eastern Apsheron Sill have the overall geometry of a right-lateral push-up structure.

Broadly north–south shortening across the range is estimated at ~ 75 km (Lyberis and Manby, 1999). This represents ~ 30% shortening of the 250-km-wide western Kopet Dagh–Greater Balkhan region. This shortening is principally Plio-Quaternary in age, based on the deposition of 4.5 km of Plio-Quaternary terrestrial clastics over an Oligocene–late Miocene marine succession; uplift was apparently diachronous from east to west, based on Pliocene strata being marine in the west but non-marine in the east (Lyberis and Manby, 1999).

7. Discussion and conclusions

The South Caspian Basin has a rigid, perhaps oceanic, basement and a ~ 20 km thick, mud-prone sedimentary succession. Both this basement and sedimentary cover are markedly different from surrounding ranges, leading to major variations in the nature and orientations of structures across the region. The South Caspian Basin is presently overthrust from all sides. At its margins, range-parallel strike–slip faults in the Alborz and Kopet Dagh indicate a westward component of motion of the South Capsian relative both to Iran and Eurasia. Earthquakes at up to ~ 80 km beneath and north of the Apsheron Sill are consistent with the South Caspian basement subducting northwards (Jackson et al., 2002).

The external folds and thrusts on the northern side of the Talysh are arcuate, convex-northwards, and pass eastwards into north–south trending thrusts that override the South Caspian Basin to the east (Fig. 2). The thrusts at the eastern margin of the Talysh cut across structures to the west, suggesting that the overthrusting of the South Caspian Basin postdates at least part of the deformation within the range (Fig. 8). Thus the Talysh takes up part of the regional Arabia–Eurasia convergence and also the westward motion of the South Caspian basement. The north–south shortening in the Talysh also means that the range moves northwards with respect to the adjacent South Caspian Basin. This translation could be taken up by a north–south trending, right-lateral, strike–slip fault. Such a structure is shown along the western margin of the South Caspian on some tectonic maps, e.g. Philip et al. (1989), but there is no evidence for it from either the seismicity record or our fieldwork observations in the Kura, Talysh or western Alborz. However, the right-lateral Sangavar Fault at the western margin of the Alborz (Berberian, 1997) has the correct orientation and sense of motion to allow the interior of the Talysh to move northwards, relative to the South Caspian basement and the Alborz (Fig. 2). Another way of achieving this motion would be by clockwise rotations of blocks of crust within the Talysh about vertical axes, which might cause the cross-cutting thrusts noted above. However, there are no palaeomagnetic data to confirm this idea. These two mechanisms for achieving the translation of the Talysh relative to the South Caspian Basin (strike–slip faulting and rotations about vertical axes) are not mutually exclusive.

Fold trains within the western South Caspian Basin are also arcuate. They link east–west compressional deformation as the South Caspian basement underthrusts the Talysh with the NNE–SSW convergence occurring in the Greater Caucasus (Figs. 2 and 6). This curvature therefore links deformation caused by the westward movement of the rigid South Caspian block with mountain building caused by the regional convergence, similar to the curvature within the Talysh. Thrusts at the junction of the Alborz and Talysh have traces that are concave towards their foreland in the South Caspian Basin. This arises from the Alborz/Talysh regions wrapping around the rigid basement to the South Caspian Basin.

Folds within the South Caspian Basin are detached from the basement by the thick mid-Tertiary Maykop interval, while the surrounding ranges deform internally within both the basement and cover. This change is seen along the Apsheron Peninsula. Here, linear thrust sheets of Mesozoic sediments in the eastern Greater Caucasus pass eastwards into the curvilinear folds of the very thick (>12 km) Oligocene–Recent South Caspian Basin succession. The Alborz deforms with multiple detachments in the sedimentary cover, including possible upper Proterozoic evaporites, Lower Jurassic coals and Tertiary evaporites.

Rigid blocks like the South Caspian basement that resist internal deformation also occur within the India–Asia collision, where the cratonic Indian plate indents into a mosaic of heterogeneous lithosphere, with strong and weak components such as Tarim and Tibet, respectively (Molnar and Tapponnier, 1981). The South Caspian Basin resembles Tarim in several ways: both regions have basement which resists internal deformation compared with adjacent areas, which are actively deforming and shedding clastics into them. Key differences are that the South Caspian basement is underthrusting at least one of its margins (Apsheron Sill) to a depth not known around Tarim, and that the South Caspian has been subsiding rapidly since at least ~5 Ma. These differences may relate to the different behaviour of regions underlain by old, continental crust (e.g. Tarim) and the highly thinned, perhaps oceanic crust under the South Caspian Basin.

The ability of the South Caspian basement to subduct under adjacent regions may lead to its eventual elimination. Speculatively, the result will be intensely imbricated slices of the South Caspian sedimentary cover, perhaps locally interthrust with mafic basement pieces, surrounded by a mosaic of highly deformed continental crust. Given subsequent time, and erosion, the end result may resemble Archaean greenstone belts and surrounding granite–gneiss terrains, albeit without the komatiites of the former or the thick cratonic keels of the latter (Ludden et al., 1986; Hoffman, 1990).

The kinematics and structural styles around the South Caspian Basin provide analogues for the early stages of older, inactive mountain belts where the initial stages of deformation and sedimentation have been overprinted and/or destroyed by the finite strain, exhumation and erosion associated with a complete orogeny. The South Caspian region especially demonstrates that a rigid block of crust within a collision zone may begin to move with respect to adjacent areas millions of years after initial collision. As it moves, it produces deformation zones with kinematics that are not predictable from the overall plate convergence. The exact style in which deformation occurs depends strongly on the nature of the crust in each area: its overall strength, pre-existing structures available for reactivation, and the stratigraphic horizons available to slip during thrusting.

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