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Dome and basin refolding and transpressive inversion along the Karatau Fault System, southern Kazakstan

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Abstract: The Karatau Fault System of southern Kazakstan forms a crustal-scale zone of strike-slip dominated transpressional tectonics which has undergone multiple phases and styles of deformation during a protracted history of reactivation from the Neoproterozoic to the Cenozoic. Ductile fabrics associated with dextral kinematic indicators are present in amphibolites along the Main Karatau Fault. The ages of the (possibly ophiolitic) protoliths and the ductile fabrics are not well constrained, but they are plausibly pre-late Riphean. Late Ordovician granites stitch thrusts and folds which deform late Riphean to Llanvirn clastics, preserved beneath a regional Late Devonian angular unconformity. This deformation may be related to a contemporary continental collision NE of the Karatau. Two phases of late Palaeozoic deformation affected the Upper Devonian and Carboniferous carbonate succession. The first phase is related to sinistral transpression along the Karatau Fault System, the second to dextral transpressional reactivation. The combination of these events produced a regional-scale dome-and-basin fold interference pattern. Similar polyphase deformation appears to have affected large areas of Central Asia and was possibly caused by the late Palaeozoic orogenies at Asia's margins, such as the accretion of Tarim and the East European Craton to Asia, and the closure of the Kazakstan Orocline. Normal faults in the Karatau are related to the formation of the Leontiev Graben, South Turgay Basin and the Yarkand–Fergana Basin in the Early to Mid-Jurassic, during renewed dextral slip along the Karatau/Talas–Fergana Fault. Late Cenozoic deformation is minor, and resulted in the uplift and incision of a Cretaceous–Palaeogene peneplain without a major tectonic overprint. Reversals in the sense of strike-slip dominated transpressive deformation across major fault systems results in *transpressive inversion*. This represents an ideal process with which to generate overprinting orthogonal fold systems, resulting in classic dome and basin interference patterns on a regional scale.

Keywords: Central Asia, Kazakstan, Karatau, transpression, folds.

The construction of Asia during the Phanerozoic is a history of accretion around the Angaran (Siberian) craton via a series of orogenies (Fig. 1). The Cenozoic addition of the Indian plate is merely one of youngest, albeit largest events in a protracted assembly of continental blocks, arcs, and accretionary complexes. What is disputed is the balance between classical Alpine-style collisions, and accretionary tectonics through time. Thus, some of the major faults in the region are interpreted variously as sutures (Zonenshain *et al.* 1990), or major strike-slip faults active during re-organization of a single continental sliver (the Kipchak arc) and its adjacent subduction-accretion complex (Şengör *et al.* 1993; Şengör & Natal'in 1996). Each successive orogeny at the Asian margin has created deformation within the continental interior of Asia, commonly by the reactivation of faults generated by earlier orogenies. Much remains to be understood about the tectonics of Central Asia, and in this paper we examine the timing, style and kinematics of deformation along one such fault zone: the Karatau Fault System of southern Kazakstan (Fig. 2). We thus aim to refine and constrain existing models for the assembly and recurrent deformation of Central Asia.

An inverted fault may be simply defined as a 'structure in which original movement sense has been reversed' (Hatcher 1995, p. 487). One of the main conclusions of our study is that transpressional reactivation of fault systems in an opposing kinematic sense to the original direction of movement (here termed *transpressive inversion*) results in classic, regional dome and basin fold interference patterns (e.g. Ramsay 1967). Such patterns are clearly preserved adjacent to the Karatau Fault System and are considered the product of two phases of sinistral and dextral transpression. Such polyphase, transpressional deformation may be a more common mechanism for producing dome and basin structures than hitherto realized.

Our original field data from the Karatau are incorporated with published literature (e.g. Ez 1954; Galitskyi 1957; Galitskyi 1971; Yarmak 1971; Patalakha & Giorgobiani 1975), aerial photographs and geological maps for the region on scales from 1:200 000, 1:500 000 and 1:1 500 000 (e.g. Abdulin & Tchimbulatov 1986; Afonichev & Vlasov 1981; Kotel'nikov 1985) to provide an overview of the regional geology. A description of the structure of the bounding fault systems on either margin of the Karatau is presented, prior to an analysis of fold geometries and patterns preserved within the central parts of the Karatau range. This is the main focus of the paper. The implications and relationships are then discussed for both Central Asia and transpressive deformation zones in general.

Geological setting and regional tectonics

The Karatau ('Black mountains') of southern Kazakstan are an elongate NW–SE-trending range extending for *c.* 400 km,

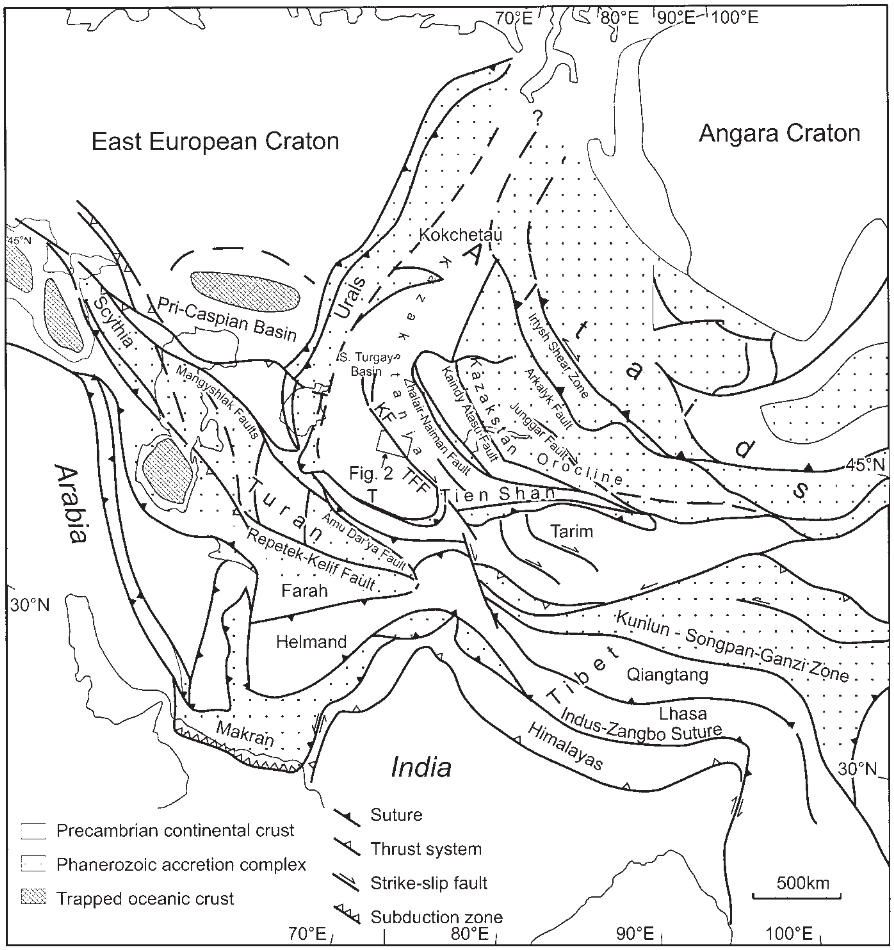

Fig. 1. Tectonic subdivisions of Central Asia and adjacent regions. Kf, Karatau Fault. TFF, Talas-Fergana Fault; T, Tamdytau region.

with a maximum elevation of 2176 m. The Syr Dar'ya Basin lies to the southwest of the Karatau, the Chu Sarysu Basin to the NE, and the South Turgay (Aryskum) Basin begins north of the present exposures in the range (Figs 1 & 2). Several faults in the Karatau are parallel to one another including the Main Karatau Fault and the Bolshoi Karoi Fault (Fig. 2), and we refer to this family of faults collectively as the Karatau Fault System. The Main Karatau Fault divides the range into the Bolshoi (Greater) Karatau to the SW and the Malyi (Lesser) Karatau to the NE. The Bolshoi Karatau has an elevation contrast of *c.* 1 km between a dissected peneplain to the SW of the Main Karatau Fault and the Chu Sarysu Basin. This uplift across the Main Karatau Fault has produced dramatic outcrop, which reveals pre-Cenozoic structures of the region without obscuring them with a major Cenozoic overprint—a common problem elsewhere in Central Asia. The Main Karatau Fault is considered to be the northwestern continuation of the Talas–Fergana Fault, with different names applied to the southern (Kyrgyzstan) and northern (Kazakstan) sections (Burtman 1964; Burtman *et al.* 1996). This fault is well known and documented due to its neotectonic strike-slip activity, and because it markedly transects the Palaeozoic structural grain of the Tien Shan (Burtman *et al.* 1996).

The Karatau/Talas–Fergana Fault appears to have originated as a single structure in the Neoproterozoic and/or early Palaeozoic history of Central Asia (Şengör *et al.* 1993), although Burtman (1964) suggested its first motion was in the late Palaeozoic. Other faults within Central Asia are subparallel to the Main Karatau Fault, and have also undergone polyphase reactivation since their origins in the Palaeozoic or earlier. This family of NW–SE-trending structures includes, from east to west, the Irtysh Shear Zone, the Junggar Fault, the Kaindy–Atasu Fault, the Zhalair–Naiman Fault, the Amu Dar'ya Fault, the Repetek–Kelif Fault and the Mangyshlak faults (Fig. 1). Models developed for the tectonic evolution of the Karatau Fault System may thus have wider regional implications for Central Asia.

Neoproterozoic rifting in the Karatau region was followed by the development of several carbonate seamounts during the early Palaeozoic, during thermal subsidence of the rifted crust (Zhemchuzhnikov 1986; Sargaskaev & Ergaliev 1988; Cook *et al.* 1991). The location of these seamounts does not appear to have been controlled by the Karatau Fault System: they occur on either side of the fault system, and have been offset *c.* 200 km dextrally by the total late Palaeozoic and younger motion along it. Late Ordovician compressional deformation terminated early Palaeozoic sedimentation in the Karatau region (Alexeiev 1998).

In the late Palaeozoic there was a major transgression over much of Central Asia, which led to the establishment of extensive carbonate platforms by the end of the Devonian. These typified sedimentation in regions from the Pri-Caspian Basin to the Chu Sarysu Basin (Fig. 1; Lisovsky *et al.* 1992). Final plate accretion had not taken place in Central Asia by this time, and a eustatic control is likely. Regionally, carbonate sedimentation across much of Central Asia ceased at various times in the Carboniferous as the result of late Palaeozoic orogenies. These included the collision of the Kazakstania continent and various arcs and microcontinents with the East European Craton to form the Uralian orogen, the collision of Tarim with the southern margin of Asia, the closure of the Kazakstan Orocline and the resultant termination of a vast subduction-accretion complex across Central Kazakstan, the complex collision of Angara and an adjacent collage of arcs and accretionary complexes with the rest of Asia (Fig. 1; Şengör & Natal'in 1996). The timing and effects of many of these events are poorly-understood. Carbonate sedimentation ceased in the Karatau in the early Bashkirian, at which time a variety of clastics were deposited including thick alluvial conglomerates on the north side of the Malyi Karatau which indicate considerable subaerial relief by this time (see Cook *et al.* 1995 for a detailed description).

Deformation in Central Asia continued in the Mesozoic as the result of successive collisions of Tethyan continental fragments with the southern margin of Asia (Şengör *et al.* 1988). These events reactivated older structures within Asia. The Cenozoic India–Asia collision represents the latest and perhaps greatest in the series of Tethyan orogenies. Strain generally decreases away from the Indus–Zangbo suture zone through Central Asia. Thus the intense seismicity and high elevations of the Himalayas, Tibet and the Tien Shan passes into less elevated zones further north, with only moderate amounts of Cenozoic deformation (Dewey *et al.* 1989). Whereas the Talas–Fergana Fault has undergone as much as tens of kilometres of late Cenozoic dextral strike-slip where it dissects the main part of the Tien Shan (Burtman *et al.* 1996), the Karatau Fault System does not possess the seismicity record, nor the geomorphology to suggest anything like such displacements (Tapponnier & Molnar 1979) and preserves its pre-Cenozoic tectonic history without being obscured by a major tectonic overprint.

Karatau fault patterns

Major faults are exposed along both margins of the Bolshoi Karatau: the Main Karatau Fault along its northeastern side and several thrusts on its southwestern flank (Fig. 2). These faults, and the faults within and marginal to the Malyi Karatau, are described below, before an analysis of the fold geometries and patterns preserved within the central parts of both the Bolshoi and Malyi Karatau (Fig. 3a). The geological evolution of the Karatau is summarized in Fig. 4, and Fig. 5 illustrates the three-dimensional structure of the Bolshoi Karatau.

Main Karatau Fault

The sub-vertical Main Karatau Fault trends NW–SE (125°) and is particularly well exposed in the Urstata section (Fig. 2), where it comprises a braided strike-slip system, several kilometres in width, with lozenges of different lithologies entrained along its length. These show complex and variable patterns of dip-slip and strike-slip deformation. Strike-slip kinematics are predominantly dextral; dip-slip mineral lineations and upright folds suggest vergence to the northeast, consistent with thrusting out of the fault zone towards the Chu Sarysu Basin. Foliation within high and low strain rocks within the Karatau Fault System forms both SE-trending and ENE-striking sub-vertical orientations; these collectively are interpreted to represent dextral shear lozenges (Fig. 3b). Lineations are broadly strike-parallel, or plunge steeply down-dip towards the south (Fig. 3c).

The lithologies within the fault zone include Riphean clastics and volcanics, Vendian phyllites and carbonates, and also serpentinites, basalts and metagabbros of unknown age (Fig. 6). Basic amphibolites are exposed immediately to the northeast of the Main Karatau Fault over an area of 20×4 km forming the Bessaz Uplift, (Figs 2 & 3a). These rocks appear to have originated as gabbro, commonly with finer-grained basic inclusions. Flasar textures are preserved in low strain zones; higher strain zones include mylonites. A variety of ductile shear sense indicators in these rocks support dextral motion, including shear bands and steeply-plunging, asymmetric folds. Muscovite and amphibole grains define mineral lineations which plunge consistently at shallow angles to either the ENE or WSW (Fig. 3c). Blocks of highly strained amphibolite are entrained in low strain metagabbro, with the implication that at least part of the strain occurred before the end of the basic magmatism which produced the amphibolite protolith. Rare leucocratic granite veins cut the amphibolites, and are not visibly strained. Zircons from plagiogranite in this zone have reported ages of 797 ± 6 Ma and 757 ± 4 Ma (Avdeev 1998). Overall, it appears that the dominant ductile fabrics in these rocks developed during dextral transpression along the Main Karatau Fault. The ages of the protoliths to these amphibolites, their ductile deformation, metamorphism and exhumation to shallow crustal levels are all poorly constrained. Collectively, however, the igneous/meta-igneous rocks resemble components of a dismembered ophiolite.

Small outliers of highly dolomitized and karstified carbonates crop out across the Bessaz Uplift. These rocks are mapped as upper Palaeozoic (Abdulin & Tchimbulatov 1986), although it is difficult to test the accuracy of this age assignment, given the alteration of the rocks. If this age is correct, it implies that the formation, deformation and exhumation of the amphibolites all took place before the Devonian. Late Riphean turbidites and rhyolitic volcanics are present in both the Bolshoi and Malyi Karatau, on either side of the Main Karatau Fault, and lack the ductile fabrics and amphibolite grade metamorphism of the Bessaz amphibolites. For this reason, we speculate that the Bessaz amphibolites were deformed during a pre-late Riphean event (Fig. 4). Within the Bolshoi Karatau, folding of lower Palaeozoic strata predates the Late Devonian angular unconformity, but we have no precise data on the kinematics or style of this deformation. It is presumably part of the late Ordovician event which generated folds and thrusts in the Proterozoic and lower Palaeozoic strata of the Malyi Karatau (see below).

Thrusts imbricate upper Palaeozoic carbonates and clastics at the southwestern margin of the Bolshoi Karatau, with an approximate transport direction towards the NE (Figs 2, 3, 5). Fault surfaces reveal multiple lineations with dip-slip motion, followed by strike-slip reactivation (both sinistral and dextral). There was possibly early ductile dextral motion on the Akuiuk thrust no. 2. The extent and significance of the thrust relationships are concealed by the post-Palaeozoic cover of the Syr Dar'ya Basin to the southwest.

Carboniferous strata adjacent to the Main Karatau Fault are locally folded, including a steeply-plunging fold pair indicating dextral shear. The folding probably post-dates Jurassic extensional faulting which down-faults uncleaved Carboniferous strata adjacent to the fault (see below). The

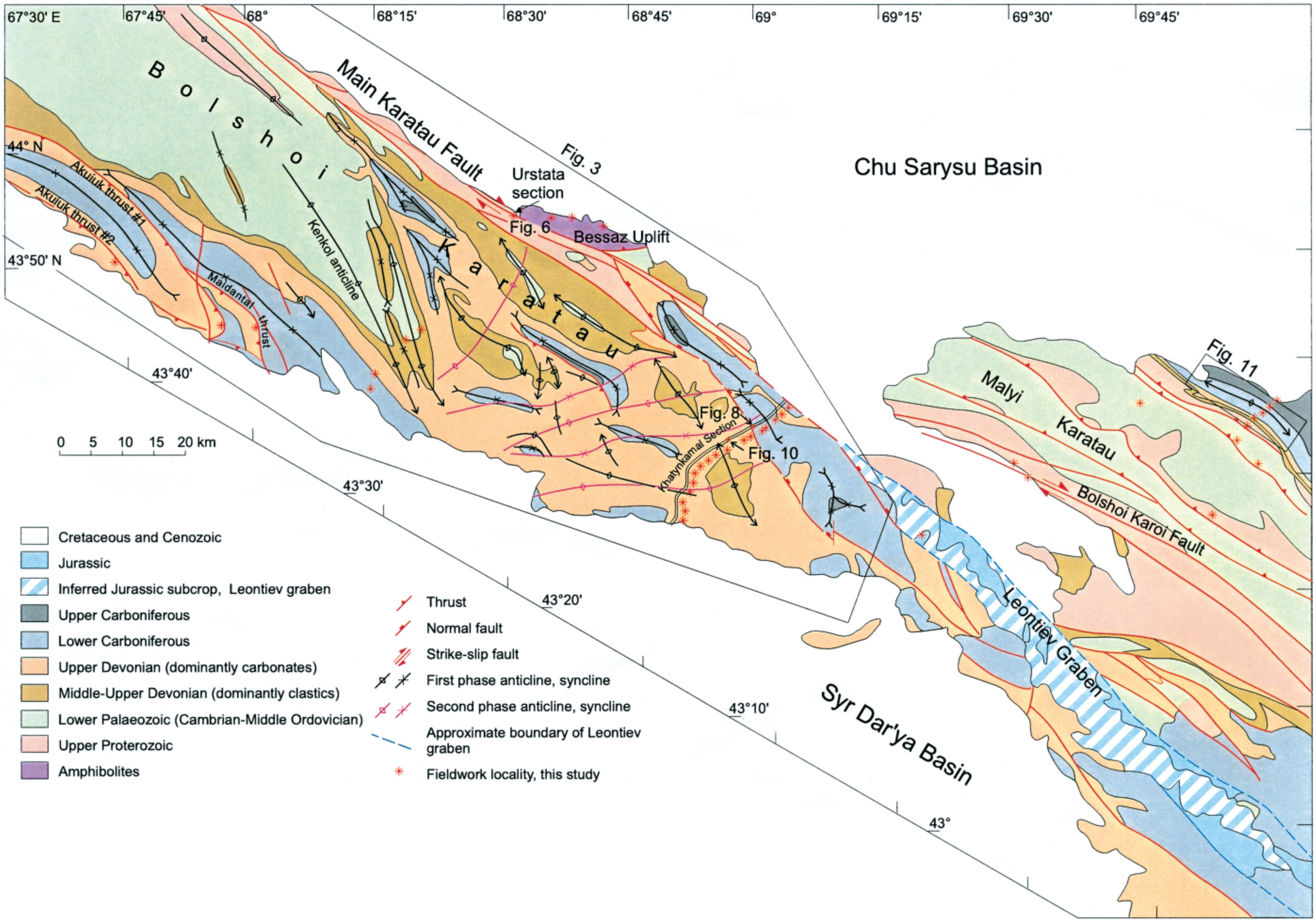

Fig. 2. Geology of the Bolshoi and Malyi Karatau and fieldwork localities mentioned in the text. Compiled from several published geological maps, including Patalakha & Giorgobiani (1975) and Abdulin & Tchimbulatov (1986), and our fieldwork observations. The Main Karatau Fault, faults bounding the Leontiev Graben and the several strands of the Bolshoi Karoi Fault collectively form the Karatau Fault System.

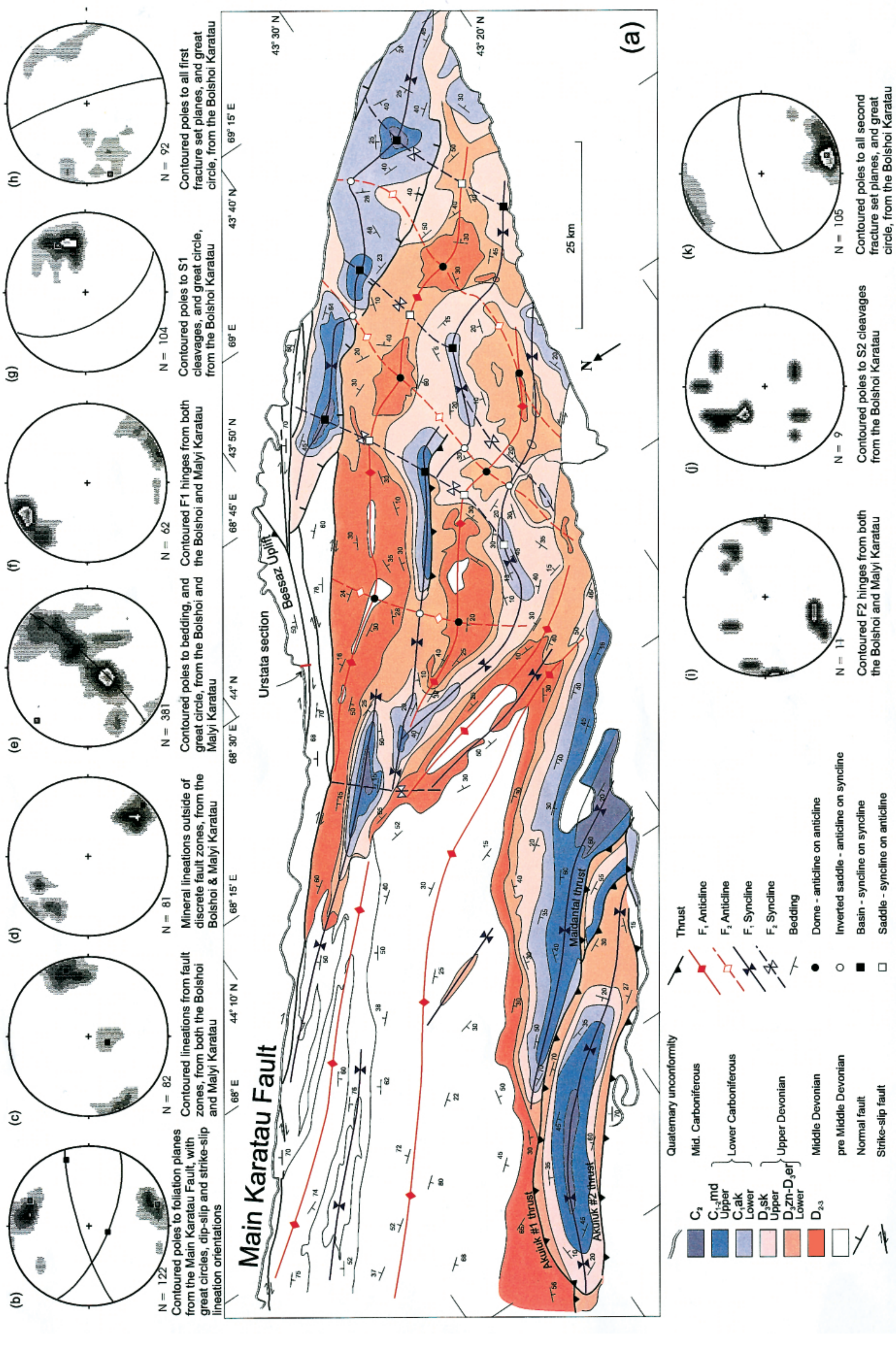

Fig. 3. Fold interference patterns, faults and structural data for the Bolshoi Karatau with mean great circle orientations on stereonets. Outcrop pattern modified from Abdulin & Tchimbulatov (1986).

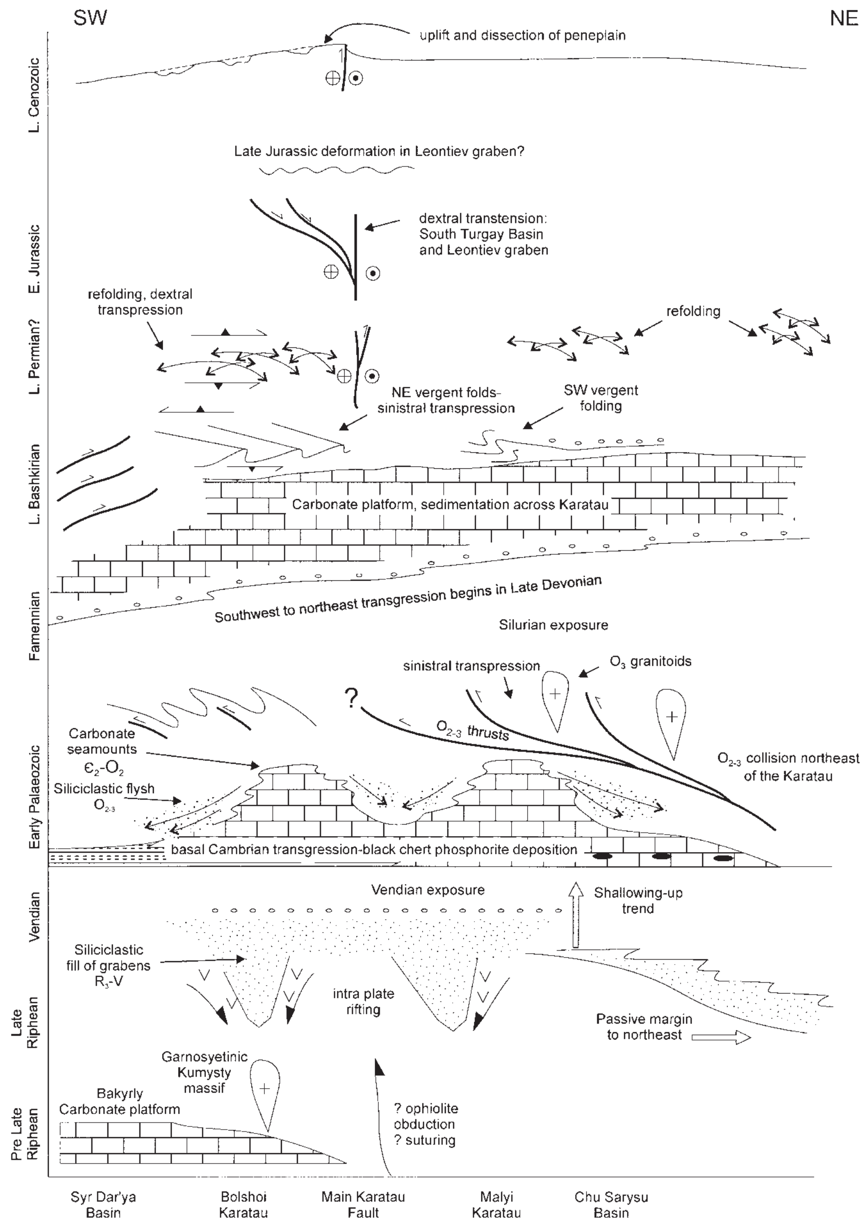

Fig. 4. Event chart for the Karatau region, and wider implications for Central Asian geology.

dextral folding is therefore plausibly Late Jurassic or Cenozoic in age and indicates that the latest phase of movement preserved along the Main Karatau Fault is associated with dextral strike-slip tectonics.

Cretaceous and Palaeogene sediments dip gently away from the Bolshoi Karatau on its southwestern flank. On the northeastern side of Bolshoi Karatau many hills have summit plateaux that are gently tilted to the SW, away from the Main Karatau Fault; these plateaux represent the remains of a dissected peneplain (Fig. 7). Local deposits of Tertiary clastics within the Bessaz Uplift vary in attitude, from sub-horizontal to dips of roughly 60° indicating continued deformation during the Cenozoic.

Bolshoi Karoi Fault

The Bolshoi Karoi Fault is a major NW–SE-trending structure developed along the southwestern side of the Malyi Karatau (Fig. 2). The northwestern part of the Bolshoi Karoi Fault is mapped as separating Riphean from Vendian clastics (Abdulin & Tchimbulatov 1986). Where examined, both units are packages of moderately deformed siliciclastic turbidites with few appreciable lithological differences across the fault. Given the lack of fossil evidence, it is thus not possible to be confident of the assigned stratigraphic ages. The Riphean strata preserve a record of early west- or NW-directed thrusting, probably contemporary with mesoscopic folding and bedding parallel cleavage, and followed by later brittle dextral strike-slip faulting on a NW–SE trend—i.e. parallel to the trace of the fault zone. The Bolshoi Karoi Fault has plausibly been active at the same times and in the same sense as the Main Karatau Fault, but does not preserve such a complete record of deformation as seen in the Main Karatau Fault and the area to its SW.

Imbricated Neoproterozoic to Middle Ordovician (Llanvirn) strata form the greater part of the exposure in the Malyi Karatau (Fig. 2). These rocks were originally deposited in a

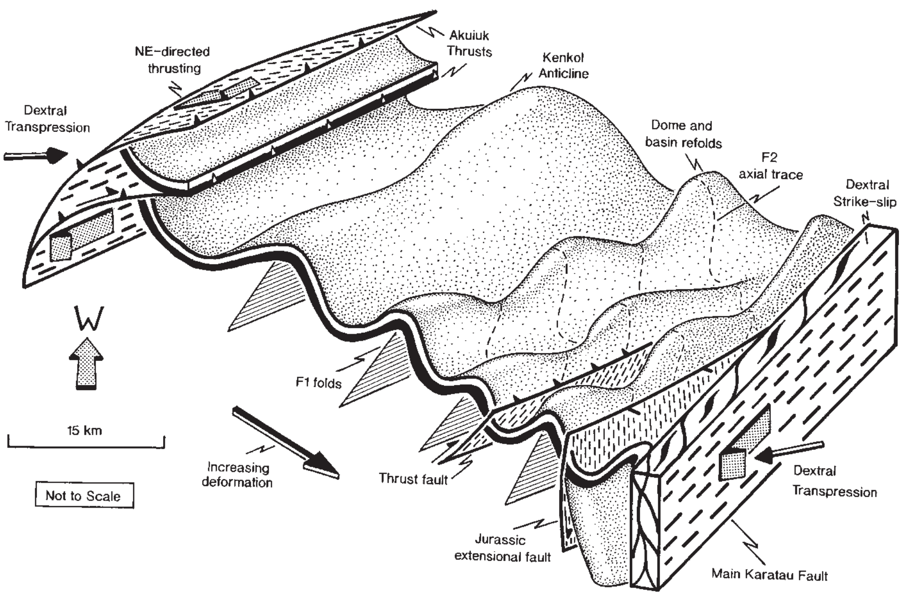

Fig. 5. Cartoon to illustrate the three-dimensional structure of the Bolshoi Karatau.

major shallowing up sequence, with Riphean turbidites at the base, passing up into shallow marine/terrestrial Vendian sandstones. Phosphorites are present in the Lower Cambrian. Thrusts trend NW–SE, with transport directions to the SW. Mineral lineations in cleaved Vendian sandstones suggest early sinistral oblique-slip followed by more brittle, distributed, dip-slip deformation (Fig. 3d). Late Ordovician granitoids dated by a Rb–Sr isochron at *c.* 447 Ma (quoted in Alexeiev 1998) stitch these thrusts in the southeast of the Malyi Karatau. This early Palaeozoic deformation is related by Şengör *et al.* (1993) to the strike-slip repetition of the Kipchak arc, now preserved across Central Asia as numerous slivers embedded in the Altaid orogenic collage between Tarim, Angara and the East European Craton. Other workers (e.g. Alexeiev 1993, 1998) link it to a continental collision between two microcontinents to the northeast of the Karatau (Fig. 1).

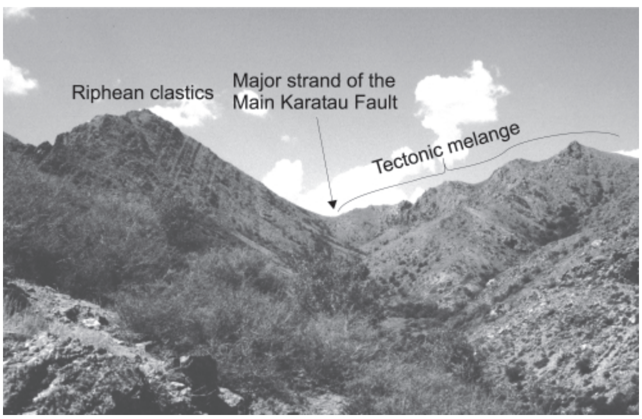

Fig. 6. Main Karatau Fault, Urstata section. View towards northwest. The maximum field of view is approximately 200 m. Location shown on Fig. 2.

Fig. 7. View south of Bolshoi Karatau, showing remnants of the dissected late Cenozoic peneplain (arrowed). The relief between the summits and the plain in the foreground is approximately 1 km.

Jurassic faulting and basin formation

The Leontiev Graben is an elongate basin of Jurassic age developed along the line of the Main Karatau Fault and to the southwest of the Bolshoi Karoi Fault (Fig. 2). The basin thus lies between the Palaeozoic exposures of the Bolshoi and Malyi Karatau. The basin fill consists of Jurassic non-marine clastics which are not generally well-exposed, and apparently lack significant structural features. Our direct observations are confined to the Lower Jurassic near the northwestern end of the basin where strata are dominantly conglomeratic, with sandstone/siltstone interbeds. Beds dip at *c.* 40° to the NNE; this is in accord with geological maps of this region (e.g. Abdulin & Tchimbulatov 1986), which indicate that Lower, Middle and Upper Jurassic strata are tilted to the northeast, and are unconformably overlain by small outliers of Upper Jurassic strata. The implications of this unconformity, if it exists as mapped, are not clear but the relationships suggest Late Jurassic tectonism and tilting.

Further to the NW in the Khatynkamal section of the Bolshoi Karatau (Fig. 2), deformation intensity generally increases towards the NE and the Main Karatau Fault, but decreases abruptly *c.* 7 km from the trace of the main fault. This region is associated with extensive calcite veining (Fig. 8), tectonic brecciation and NE-dipping faults. The faults in this area appear to be extensional, bringing less-deformed, lower Carboniferous carbonates down to the NE (Figs 2, 5). Adjacent to the Main Karatau Fault, there are exposures of steeply NE-dipping, probably overturned sediments, which lack the folds, cleavage or major vein sets found in the Upper Devonian sediments to the south. We relate this extensional faulting to deformation at the northwestern limit of the Leontiev Graben which thus implies a Jurassic age.

Fig. 8. Breccia zone with extensive calcite veining, northern part of the Khatynkamal section, Bolshoi Karatau. This zone occurs within a region of extensional faults, of probable Jurassic age.

To the north of the Karatau, the South Turgay Basin (Figs 1, 9) contains similar Jurassic rocks. Extension created the Turgay Basin in the Mesozoic. Most accounts have the earliest syn-rift deposits as approximately Early Jurassic (Kuandykov *et al.* 1992; Korchagin *et al.* 1996), with the greater part of the extension over by the end of the Mid-Jurassic. By this time a maximum of *c.* 2500 m of non-marine clastics had accumulated, including bituminous shales. Further SE along the Talas–Fergana Fault, the Yarkand–Fergana Basin is an elongate basin with a thick (*c.* 5000 m) Lower and Middle Jurassic succession in its Chinese portion, where it is known as the Kuzigongsu pull-apart (Hu Wangshui 1995). This basin is not the same structure as the better known Fergana Basin further west.

Our model for the evolution of the South Turgay, Leontiev and Yarkand-Fergana basins relates all three basins to dextral strike-slip on the Karatau/Talas–Fergana Fault (Fig. 9). The splay of normal faults in the South Turgay Basin formed as a trailing imbricate fan (Woodcock & Fischer 1986) at the northern limit of the fault system. The Leontiev Graben and the Yarkand-Fergana Basin formed as dextral transtensional basins at right-stepping jogs in the fault system. Although Burtman (1980) regarded Jurassic slip along the Talas–Fergana Fault as insignificant, the presence of Lower–Middle Jurassic transtensional basins along its length suggests that there was considerable deformation at this time, although the exact slip is not known for any segment of the fault system.

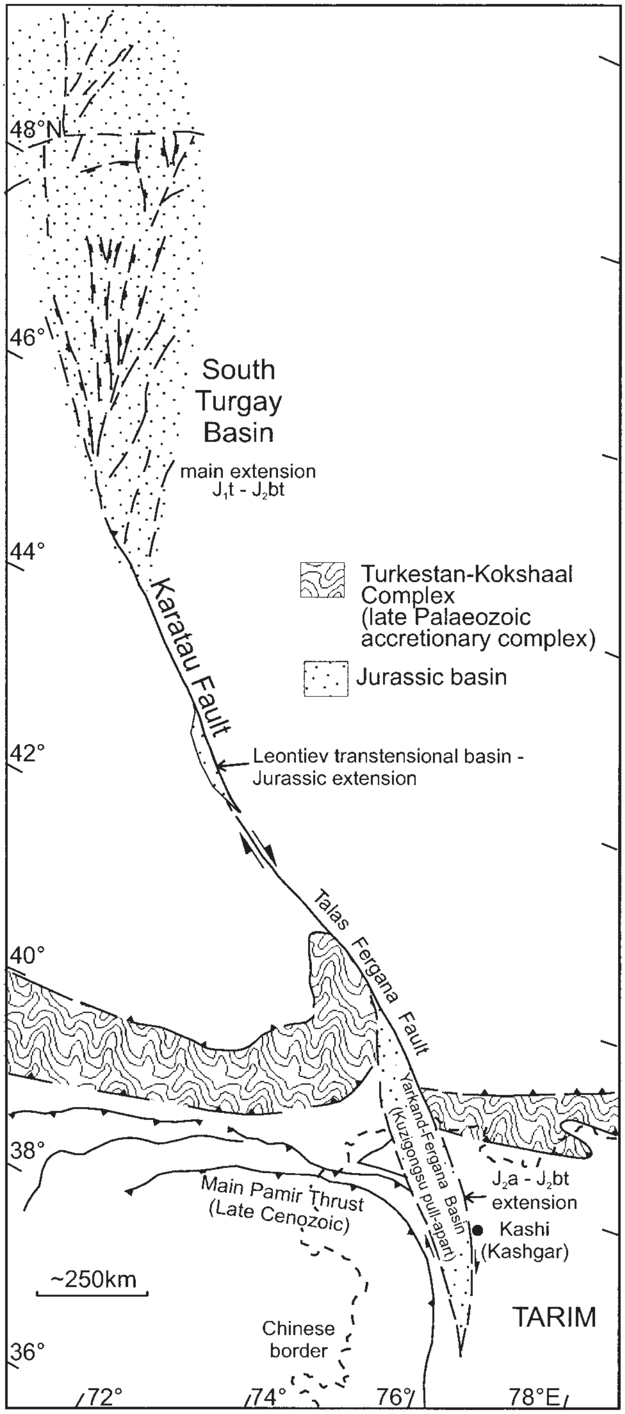

Fig. 9. Early–Mid-Jurassic evolution of the Karatau/Talas–Fergana Fauilt as a dextral strike-slip system. The South Turgay Basin formed as a trailing imbricate fan of normal faults at the northwestern end of the Karatau/Talas–Fergana Fault; the Leontiev Graben and Yarkand–Fergana Basin originated as trantensional basins. The total offset of the Talas–Fergana Fault (late Palaeozoic, Mesozoic and Cenozoic) is shown by the displacement of the late Palaeozoic accretionary complex of the southern Tien Shan.

Karatau fold patterns

An observation of our fieldwork is that sedimentary conglomerates present at the base of the upper Palaeozoic succession, and Mesozoic karstic breccias within the lower Famennian carbonate unit in the central part of the Bolshoi Karatau, have been commonly mis-identified by previous workers as tectonic breccias. Existing maps of the area, e.g. Patalakha & Giorgobiani (1975); Afonichev & Vlasov (1981), are seriously inaccurate in this respect as they show widespread low-angle thrust faults which are not depicted as disrupting the stratigraphy. We consider these mapped faults to be spurious, and they are omitted on Figs 2 & 3a.

The fold generation nomenclature (F_1, F_2) used in the following description refers only to the deformation that affected the upper Palaeozoic strata. We are not clear how many pre-late Palaeozoic deformation events affected the region, and so have not erected a scheme which covers all events since the Precambrian.

Bolshoi Karatau

The first major set of folds (F_1) to develop in the Bolshoi Karatau are upright, broadly NW–SE-trending open-closed folds (Figs 3a, e, f and 5) with moderately to steeply SW-dipping axial planes. The wavelength of these sub-horizontal-plunging major folds is in the order of 12–15 km in the central part of the Bolshoi Karatau, and this decreases (to <10 km) towards the fault systems on either margin (Fig. 3a). Associated with the decrease in fold wavelength is a sequential rotation of the fold axial traces into sub-parallelism with the fault systems. F_1 fold axial traces consistently form in a clockwise sense to the Main Karatau Fault, with angles varying from 40° in the central part of the Bolshoi Karatau to less than 20° at both the NE and SW margins. Similar sigmoidal fold traces are observed within other major strike-slip and transpressional systems such as the Dead Sea Transform and Lebanese restraining bend (e.g. Griffiths *et al.* 2000). The arrangement is commonly considered to reflect increasing deformation towards the marginal faults, (e.g. Price & Cosgrove 1990; Jamison 1991) and indicates the close relationship between fold generation and movement on the faults. In addition to the clockwise sense of folding, major axial traces are consistently overprinted in a clockwise sense by parasitic minor fold hinges. The NW–SE-trending, steeply SW-dipping S_1 cleavage (Fig. 3g) transects the measured F_1 hinges in a consistent clockwise sense, with a transection angle of 12° measured from a mesoscopic, F_1 fold that was mapped in detail. The sense of cleavage/bedding vergence reverses across the gently NW-plunging fold hinge, indicating coeval development. Rocks become cleaved approximately 10 km from the trace of the Main Karatau Fault as deformation intensifies towards this structure, cleavage verges to the NE. The clockwise transection of major folds by minor folds and cleavages supports sinistral transpressive deformation (see Sanderson & Marchini 1984), which intensifies into the marginal fault systems, resulting in axial planar rotation. Folding along the SW margin of the Bolshoi Karatau is associated with NE-directed thrusting with the synclines forming in the hangingwall of the thrusts (Fig. 3a). The relationship of folding to strike-slip and thrust faults supports the model of transpressional deformation.

Upper Palaeozoic carbonates are also deformed by an early, sub-vertical, fracture set which trends approximately SSE (Fig. 3 h). These mode I–II fractures are commonly associated with a calcite vein fill. Their origin is uncertain, but they have a similar trend to F_1 axial planes and associated cleavage, and lie parallel to mesoscopic F_1 axial planes at outcrop. We therefore suggest that they may represent longitudinal fractures with respect to the F_1 folds.

No indicators of syn-sedimentary tectonic activity were noted within the Upper Devonian to Lower Carboniferous carbonate succession, consistent with the previous interpretation that these rocks were deposited in a platform setting (Cook *et al.* 1995). The appearance of clastics, including alluvial conglomerates, in the early Bashkirian marked the end of carbonate sedimentation. These clastics are the best constraint of the maximum age of the first phase of late Palaeozoic deformation in the Karatau (Fig. 4): they are the youngest rocks deformed by the NE-directed thrusts at the southwestern margin of the present range and by the F_1 folding event (Fig. 3a).

The first generation of folds in the upper Palaeozoic strata was later orthogonally re-folded along upright, gentle-open, NE–SW-trending (F_2) folds (Figs 3a, 3i, 5), resulting in a classic dome and basin interference pattern (Ramsay 1967). The axial traces of F_1 folds are clearly deflected and folded around the F_2 folds, verifying the deformation chronology and indicating that the two sets of fold axial planes are not precisely orthogonal to one another (Thiessen & Means 1980; Thiessen 1986) (Fig. 3a). The F_2 fold hinges are sub-horizontal and have wavelengths of *c.* 20 km, although this typically diminishes towards the marginal fault systems. In the central part of the Bolshoi Karatau, F_2 axial traces are typically developed at 45° in an anticlockwise sense to the marginal faults, with this angle reducing towards the southeastern boundary. Few minor structures are observed which may be directly related to the later phase of folding, although a second cleavage (S_2) is locally developed in the carbonates (Figs 3j, 10). ENE-trending minor F_2 fold hinges with associated S_2 cleavage locally overprint the earlier minor F_1 folds and S_1 cleavage. The second cleavage typically strikes NE–SW, dips moderately towards the SE and apparently transects the map scale F_2 axial traces in an anticlockwise sense. The anticlockwise transection angles, coupled with evidence of dextral shear preserved along the marginal faults, strongly suggests dextral transpressive reactivation of the Karatau Fault System.

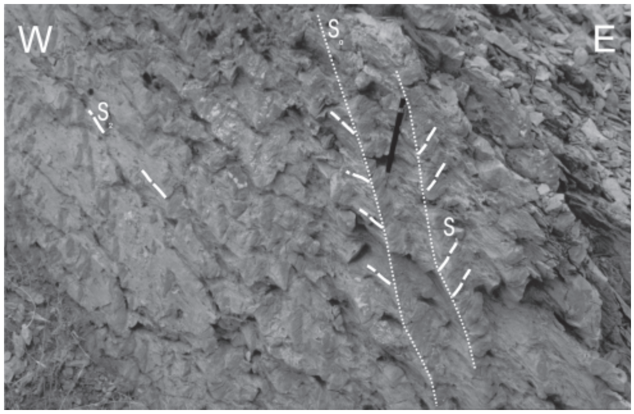

Fig. 10. Two generations of cleavage developed in Upper Devonian limestones, Khatynkamal section, Bolshoi Karatau. S_0, bedding plane; S_1, first-generation cleavage; S_2, second-generation cleavage. Location shown on Fig. 2.

There is a second, ENE-trending sub-vertical fracture set (Fig. 3k), which offsets and postdates the SSE set, and is locally associated with dextral tension gashes. These mode I–II fractures are also typically filled by calcite veins. We tentatively interpret this fracture set, which parallels the trend of F_2 axial planes, as longitudinal fractures with respect to the F_2 fold phase.

The timing of the second fold phase is not well constrained, although it does appear to pre-date structures associated with the Jurassic Leontiev Graben. Burtman (1980) suggested a Late Permian age for the initiation of dextral movement along the Talas–Fergana Fault to the southeast. The second phase of folding in the upper Palaeozoic strata of the Karatau has an orientation and geometry consistent with dextral transpression, and so we tentatively also date this deformation as Late Permian (Fig. 4). Better constraints are clearly needed for the timing of both F_1 and F_2 in the upper Palaeozoic strata of the Karatau region.

Malyi Karatau

Upper Palaeozoic strata crop out along the northeastern side of the Malyi Karatau (Figs 2, 11), with a basal angular

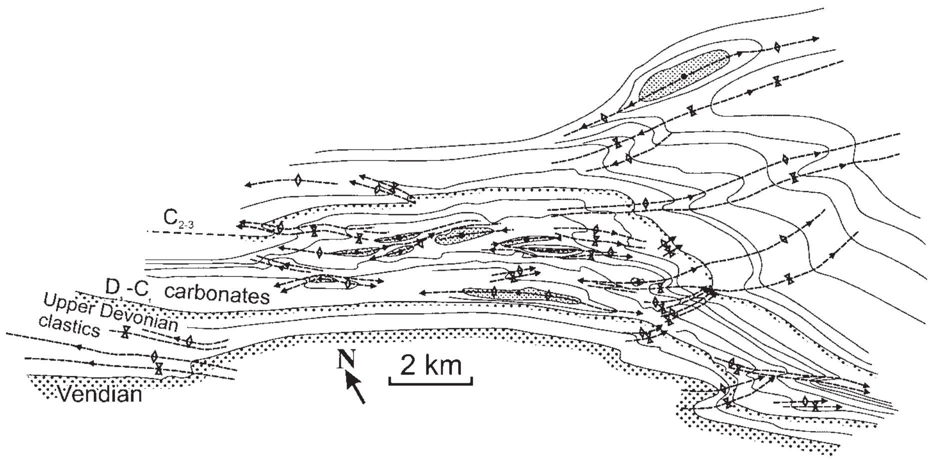

Fig. 11. Map of deformed Upper Palaeozoic strata, Malyi Karatau. Derived from an aerial photograph with a scale of 1:25 000, data in Patalakha & Giorgobiani (1975) and our fieldwork observations. Location shown on Fig. 2.

unconformity over the Riphean–Llanvirn succession. The oldest strata are Famennian alluvial conglomerates, overlain by sandstones and Tournaisian carbonates. Carbonates from the Lower Carboniferous section are overlain by thick Bashkirian alluvial conglomerates which dip moderately to the NE. Deformation is concentrated in Visean limestones, possibly because they are less massive than underlying and overlying strata. The main, first phase of deformation in these rocks consists of upright, SW-verging F_1 folds. The limbs of these gentle–open folds dip gently towards the NE and SW, with the sub-horizontal hinges trending at 127°. The F_1 fold hinges are gently curvilinear about the horizontal, resulting in periclinal dome and basin outcrop patterns on a kilometre scale. Although these structures are locally overprinted by upright (F_2) folds with SW- or SSW-trending axes, the outcrop pattern is not considered a product of simple fold interference as no systematic dome and basin geometries are observed (Fig. 11). The deformation apparently intensifies downwards into the lower part of the Carboniferous, suggesting that variable displacement in underlying zones of deformation may result in the observed fold patterns (see Alsop & Holdsworth 1993; Alsop *et al.* 1996). Thus, whilst F_1–F_2 refolding is not considered to produce the major closed outcrop patterns described above, it is plausible that each set of folds corresponds in age and origin with its counterpart in the Bolshoi Karatau.

Discussion and conclusions

Implications for regional tectonics

Fieldwork observations from the Karatau indicate a regional polyphase deformation history with the oldest and most intense structural fabrics present in the ductile foliations and shear zones within basic amphibolites of the Bessaz Uplift. Such metamorphism and deformation is absent from other rocks in the region, including late Riphean clastics and volcanics, and we therefore tentatively date this deformation as pre-late Riphean (Fig. 4), although it is possible that the amphibolites represent an exotic fragment of crust, juxtaposed against other fault rocks entirely during Phanerozoic deformation.

According to Şengör & Natal'in (1996), the Karatau/Talas–Fergana Fault originated in the Mid- to Late Ordovician as a sinistral strike-slip structure, which juxtaposed segments of an elongate active continental margin, named the Kipchak arc. This event was part of a much more widespread episode of sinistral strike-slip deformation, along an arc system postulated to have been *c.* 7000 km long before strike-slip repetition. Our data from the Karatau are consistent with major compressional deformation in the late Mid- to Late Ordovician, with a small component of oblique sinistral motion, but provide no support for major sinistral strike-slip along the Main Karatau Fault or sub-parallel structures. An alternative explanation is that the thrusts, folds and cleavage in Riphean to Llanvirn strata result from a collision to the NE of the Karatau (Alexeiev 1998; Fig. 1). The Zhalair–Naiman Fault (Fig. 1) is a candidate for the suture zone of this collision. The dextral, ductile fabrics in the amphibolites of the Bessaz Uplift require a Neoproterozoic or early Palaeozoic event not present in the regional kinematic model of Şengör & Natal'in (1996). If the basic rocks represent components of a dismembered ophiolite then the intense deformation along the fault zone possibly conceals a suture zone.

The first phase of folds to affect the Devonian–Carboniferous succession may be related to either or both of two orogenies taking place in adjacent areas of Central Asia in the late Palaeozoic. The collision of the northern, passive margin of the Tarim microcontinent (Fig. 1) with the southern margin of Asia began in NW China in the latest Devonian, and was diachronous from east to west as the intervening ocean closed in a scissors-like manner (Allen *et al.* 1993). This created an orogen preserved within the southern parts of the modern Tien Shan. Most of the collision-related deformation in the western Tien Shan is Late Carboniferous in age, as is the regional termination of carbonate sedimentation across Kazakstania (Burtman 1975).

An alternative cause of the first phase of late Palaeozoic deformation in the Karatau is the tightening of the Kazakstan Orocline (Fig. 1), itself part of the wider Altaid orogeny (Şengör & Okurogullari 1991; Şengör & Natal'in, 1996). One aspect of Şengör & Natal'in's (1996) model for the Altaids is that it predicts widespread Late Carboniferous dextral strike-slip on the Irtysh Shear Zone (Fig. 1) and sub-parallel structures. This is contradicted by our interpretation of sinistral transpression in the Karatau at this time. Recent work on the Irtysh Shear Zone itself has produced Late Carboniferous to Early Permian ^{40}Ar–^{39}Ar ages for granites and shear fabric muscovites associated with sinistral shear on this fault system—with no indication of earlier dextral motion of any age (Melnikov *et al.* 1997).

The second fold phase to affect the upper Palaeozoic strata may correlate with the Late Permian, dextral strike-slip identified to the southeast, on the Talas–Fergana Fault (Burtman 1980). The regional cause of this folding and strike-slip faulting is unclear. Much of Kazakstan and northwest China was affected by Late Permian strike-slip deformation, of both dextral and sinistral senses. In places this is associated with extension, such as the 'intermediate complex' rift zones that underlie large parts of Turan (Davlyatov & Pak 1987), and the Junggar Basin of NW China (Allen *et al.* 1995). There are local mid Permian compressional structures too, such as at the southeastern termination of the dextral Ketuer Fault in the northern Tarim Basin (Wang Xiepei & Yan Junjun 1995).

Early–Mid-Jurassic extension in the South Turgay Basin, Leontiev Graben and Yarkand–Fergana Basin was related to reactivation of the combined Karatau/Talas–Fergana Fault. The location, structure and orientation of these basins are consistent with an origin during dextral slip along the fault system. Together, these basins and the intervening fault segments form part of a linked fault system over 2500 km long (Fig. 9). Mesozoic intracontinental deformation in Central Asia has been related to compression created by the docking of a series of continental fragments with Asia, such as Farah, Qiangtang, Helmand and Lhasa (Fig. 1). Each of these blocks appears to be derived from Gondwana, and was transported northwards across branches of the Palaeo- and Neo-Tethyan oceans (Şengör *et al.* 1988; Hendrix *et al.* 1992). A curious feature of the Early–Mid-Jurassic basin formation along the Karatau/Talas–Fergana Fault is that it does not coincide with the time of accretion of these continental blocks. Farah and Qiangtang collided with Asia in the Late Triassic, while Lhasa and possibly Helmand accreted in the Late Jurassic. A similar problem relating the timing of deformation to continental collisions occurs in northwest China. Vincent & Allen (2001) identified more Mesozoic deformation events in northwest China than can be accounted for by a simple, one-to-one match with known collisions, and proposed that some of the Mesozoic compressional deformation in Central Asia took place in a retroarc setting, north of contemporary compressional Andean-type margins at the southern edge of Asia.

Uplift of Tertiary sediments SW of the Main Karatau Fault suggests at least some Cenozoic movement on the fault, but the seismicity record of this area is much less intense than the Talas–Fergana Fault to the southeast (Tapponnier & Molnar 1979).

Implications for fold interference patterns

The Palaeozoic rocks exposed within the Bolshoi Karatau form part of a well-defined stratigraphy which elucidates the structural map patterns. This Palaeozoic stratigraphy both displays and highlights a large-scale (*c.* 20 km) dome and basin map pattern (Figs 3a, 5), which we interpret as an example of a classic interference geometry generated during two distinct phases of folding (Ramsay 1967). The superposition and coincidence of similar fold forms generates in-phase constructive interference patterns in which amplitudes may be exaggerated i.e. anticline on anticline producing domes, syncline on syncline resulting in basins. Refolding by dissimilar fold geometries leads to out-of-phase destructive interference geometries in which amplitudes may be diminished i.e. syncline on anticline producing saddles, whilst anticline on syncline results in inverted saddles.

The regular and systematic spacing of structures generated by fold interference is different to that produced during

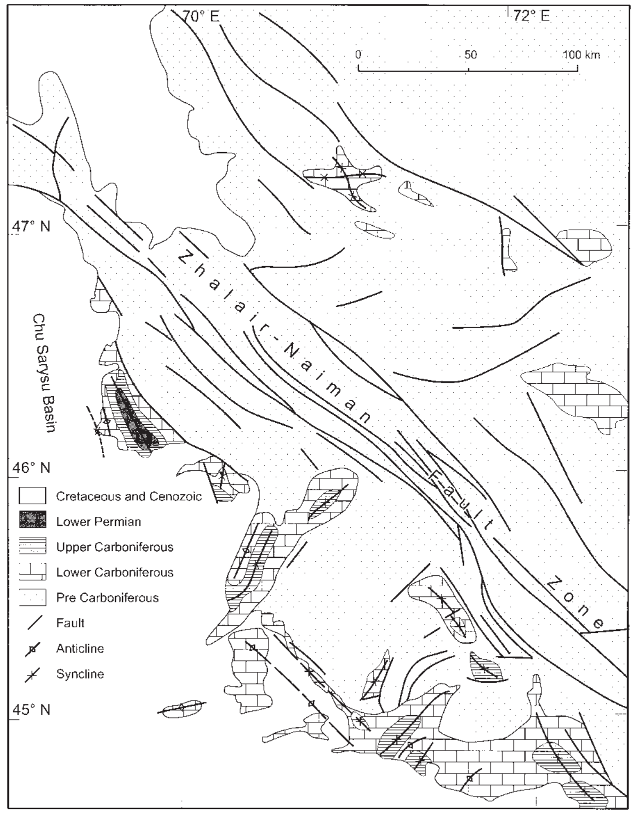

Fig. 12. Sketch interpretation of refold patterns exposed near the margin of the Chu Sarysu Basin. From Afonichev & Vlasov (1981).

progressive, constrictive deformation in which domes and basins are associated with diversely orientated axial planes and arcuate fold hinges apparently lacking distinct spatial order (e.g. Ghosh 1993; Oliver 1994). The fold geometries observed in the Bolshoi Karatau are typically open-closed folds and therefore may not be considered in terms of sheath fold models which require intense progressive deformation to generate fold hinge rotation with associated inter-limb tightening (see Alsop & Holdsworth 1999 for a review).

By analogy with the Main Karatau Fault, other basement faults in Central Asia are likely to be wide, complex structures, with polyphase deformation histories and major roles in controlling fluid flow. Of particular interest is the relationship of folding to such faults: are folds confined to deformation envelopes close (tens of kilometres) to the major faults, or do they exist over much wider areas? Analysis of 1:200 000, 1:500 000 and 1:1 500 000 geological maps of Central Asia indicates the presence of refolded Devonian and Carboniferous strata over 1000 km from the Karatau, such as in the Kokchetau (Kokchetav) region of northern Kazakstan (Fig. 1; Afonichev & Vlasov 1981). Other examples are closer, for example at the northern margin of the Chu Sarysu Basin (Fig. 12; Afonichev & Vlasov 1981), and in the Tamdytau region of Uzbekistan (Drew 1993). The geographical spread of these examples suggests that a lot of the sedimentary basins in Central Asia could have been affected, from the Pri–Caspian to Tarim. Pavlov *et al.* (1988) noted that the Upper Devonian strata of the Tengiz oil field in the Pri–Caspian Basin were folded into a large domal anticline, 17×24 km across with an amplitude of 300–400 m. At present it is unknown precisely how much these folds and refolds have in common, with

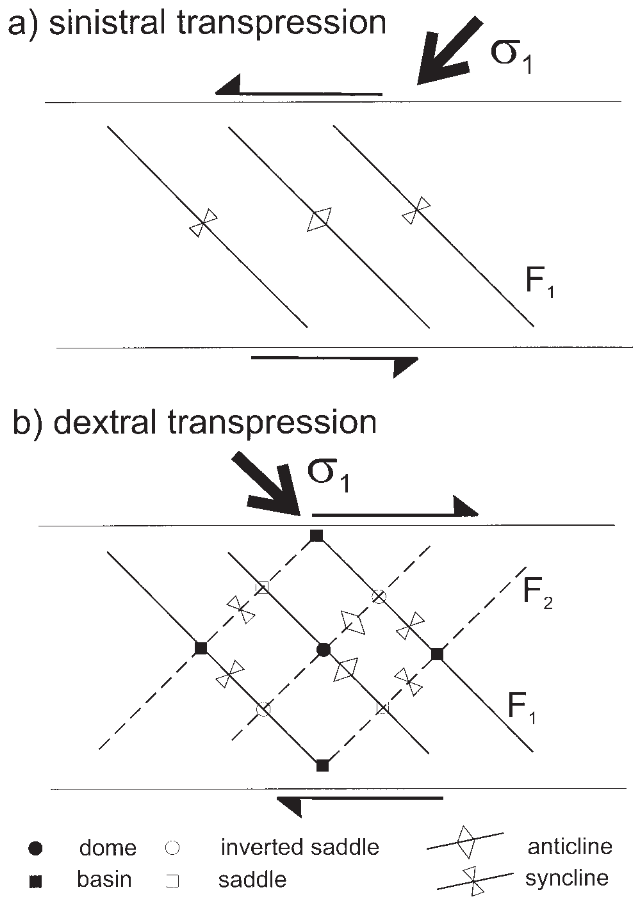

Fig. 13. Cartoon to illustrate how dome and basin fold interference patterns may be generated by transpressive inversion involving successive phases of transpressional deformation with opposing senses.

respect to their age, style, orientation and origin. However, we speculate that the origin of all these fold interference patterns is likely to be the late Palaeozoic collisions which welded the East European Craton, Kazakstania, Tarim, the Angaran craton and the largely-unknown basement of Turan to each other.

A general point of transpressive inversion and reactivation via general switching of the σ_1 and σ_3 stress axes is that it forms the perfect vehicle for producing (possible large-scale) dome and basin interference patterns. Reactivation of transpressional systems in a reverse sense, i.e. sinistral followed by dextral (or vice versa) is a simple and effective mechanism which may operate on all scales from regional (e.g. Holdsworth 1994) to outcrop (e.g. Alsop *et al.* 1998). This process will generate upright folds trending *c.* 45° to strike-slip-dominated systems that will be overprinted by the second set of folds which form at *c.* 45° in the opposing sense (Fig. 13). It is thus possible to generate large-scale upright fold systems that are broadly orthogonal to one another. The fact that strike-slip systems are sub-vertical and generate gently-plunging fold hinges means that the map view provides us with the perfect horizontal 'cut' through the domes and basins.

Dome and basin patterns of a similar scale are reported from the high Atlas of Morocco, where de Sitter (1952, 1964) notes the presence of both sinistral and dextral strike-slip faults coupled with thrusting. Elsewhere, culminations and depressions along the hinges of individual folds may be the product of variable strain intensity (e.g. Wood & Oertal 1980). However, this view has been recently challenged by Baird & McCaffrey (1999) who, with the support of isotopic dating, suggest that such structures may, at least in part, be the product of two distinct phases of deformation producing fold interference patterns. Improved isotopic age dating techniques enable the increasing recognition of such distinct and discrete deformation events. Detailed field observation, coupled with more refined dating, will result in a greater understanding of evolving deformation systems and enable the recognition of distinct deformation pulses. Transpressive inversion may thus represent a widely applicable mechanism of generating large-scale dome and basin fold interference patterns in zones of major crustal deformation.

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