Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia

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A new tectonic model, postulating the growth of giant subduction-accretion complexes along a single magmatic arc now found contorted between Siberia and Baltica, shows that Asia grew by 5.3 million square kilometres during the Palaeozoic era. Half of this growth may have occurred by the addition of juvenile crust newly extracted from the mantle, supporting models of considerable continental growth continuing throughout the Phanerozoic eon.

THE orogenic architecture of the Altaids—the late Proterozoic to early Mesozoic orogenic belts surrounding the ancient core region of northern Asia, the Angaran craton (Fig. 1)—has long been recognized as different from that of classical collisional orogens such as the Alps and the Himalayas. The main difference lies in the paucity in the Altaids of extensive ancient gneiss terrains representing former continental fragments, and the molasse-filled foredeeps that generally form between them. The Altaids are formed mainly from material commonly found in present-day subduction-accretion complexes, intruded by vast plutons of mainly magmatic arc origin and covered in places by their volcanic derivatives. Owing to the absence of laterally continuous rock groups and structures that can be used as structural markers to outline the large-scale architecture of the mountain belt, we introduce the 'magmatic front' (that is, the sharply defined oceanward limit of arc magmatism) as a new kind of structural marker to follow the trend-line of the orogen in the Altaids. Doing this allows us to see that the allegedly independent orogens within the Altaid edifice, such as the Ural, Tien Shan, Kazakhstan, Altay/Sayan and Mongol–Okhotsk, may instead have evolved along a single subduction zone, a part of which was located in front of a migratory island arc, called the Kipchak arc. This arc rifted from a combined Baltica/Siberia hinterland in the Cambrian period and became multiply bent (in the manner of an 'orocline') as a consequence of the convergence of these two cratons in the late Palaeozoic. As the Altaid orogen evolved, magmatic arc axes migrated into growing subduction-accretion complexes in front of the Kipchak and the Altay–Mongol arc systems, thereby enlarging the continental crust.

These subduction-accretion complexes added ~5.3 million km^2 of material to Asia, half of which may be of juvenile origin. This supports interpretations of considerable continental growth during the Phanerozoic, and the Altaid addition to the continental crust may make up as much as half of all the new material added to the continents during the Palaeozoic.

Using magmatic fronts as structural markers may also help in understanding the poorly known Precambrian collages that comprise the cratons, such as the Pan-African system in Arabia. Our reconstruction of Altaid evolution shows that unless detailed geological reconstructions of orogenic collages are attempted, it is unlikely that reconstructing past positions of continental pieces by using only palaeomagnetic, palaeoclimatological and palaeobiogeographical data will have much success.

The Altaid orogenic collage

Suess[1] recognized that Asia had grown peripherally mainly to the west and south of the Angaran nucleus during the Palaeozoic, and he named the resulting orogenic collage the Altaids (Fig. 1). Since then allegedly independent orogens have been distinguished within the Altaids[2–19]. From east to west, these are the Mongol–Okhotsk (units 23 and 24 in Fig. 2), Altay/Sayan (units 13 to 22 in Fig. 2), the Kazakhstan 'microcontinent'[6] (or Kazakhstania[20]: units 1–12 in Fig. 2, north of 45° N), Tien Shan (units 1–5 and 10 in Fig. 2, south of 45° N), and the Urals (Ural plus unit 1 in Fig. 2)[21]. Even in the first plate-tectonic interpretation of the Urals, Hamilton[22] suggested that the Ural, the Kazakhstan uplands and the Altay/western Sayan (Fig. 1) might be parts of a single orogenic system with a sharply bent orocline. Hamilton's view has remained unpopular, despite the growing awareness that the peri-Angaran Palaeozoic orogenic belts are strikingly similar to those farther west[22–24].

It has been recognized recently that much of the Altaid collage is formed dominantly from giant Palaeozoic subduction-accretion complexes, surprisingly uniform in timing and style of tectonism, and from the development of subduction-related sedimentation and magmatism, together forming a distinctive orogenic style reminiscent of the circum-Pacific systems called elsewhere 'Turkic-type'[25–27]. The presence of independent orogenic systems in the Altaids is therefore questionable, especially because the enormous amount of clastic material scraped off into giant accretion complexes must have come from a major continent. If the Kazakhstanian microcontinent is 'free floating', this would require a source well away from major continents.

We first review evidence to support the suggestion that all the orogenic belts forming the Altaid collage have evolved dominantly along a single subduction zone that developed during the Cambrian along the eastern margin of a unified Baltico-Siberian continent (Fig. 3*a*). This hypothesis revives Hamilton's suggestion, albeit with an improved geometry, and also combines the peri-Angaran 'Baykalides' and the 'pre-Uralides' into a single Late Precambrian collision orogen flanking the Baltico-Siberian continent to the west.

Definition of tectonic units in the Altaids

Even in the last century it was well known that the architecture of the Altaids was dominated by 'schists, slates, mafic igneous rocks, and granites'[1,28], since interpreted to reflect the dominance of large former subduction-accretion complexes[25–27]. The monotony of their lithologies, dominated by basalt, chert and turbidites, and the nearly chaotic aspect of their penetrative internal structure make it difficult to find markers in large subduction-accretion complexes by which to outline their large-scale structures. This problem has hindered recognition of the architecture of the Altaids.

To find and map the lateral continuity of large palaeotectonic units, the smallest independently functioning plate-tectonic apparatus, we use magmatic fronts of former arc systems. These fronts are the oceanward limits of magmatism in arcs, and we choose them as structural markers because they tend to be sharp[29] and temporally persistent on a scale of tens of millions

FIG. 1 The Altaid tectonic collage in its Eurasiatic setting with the key geographical localities referred to in the text.

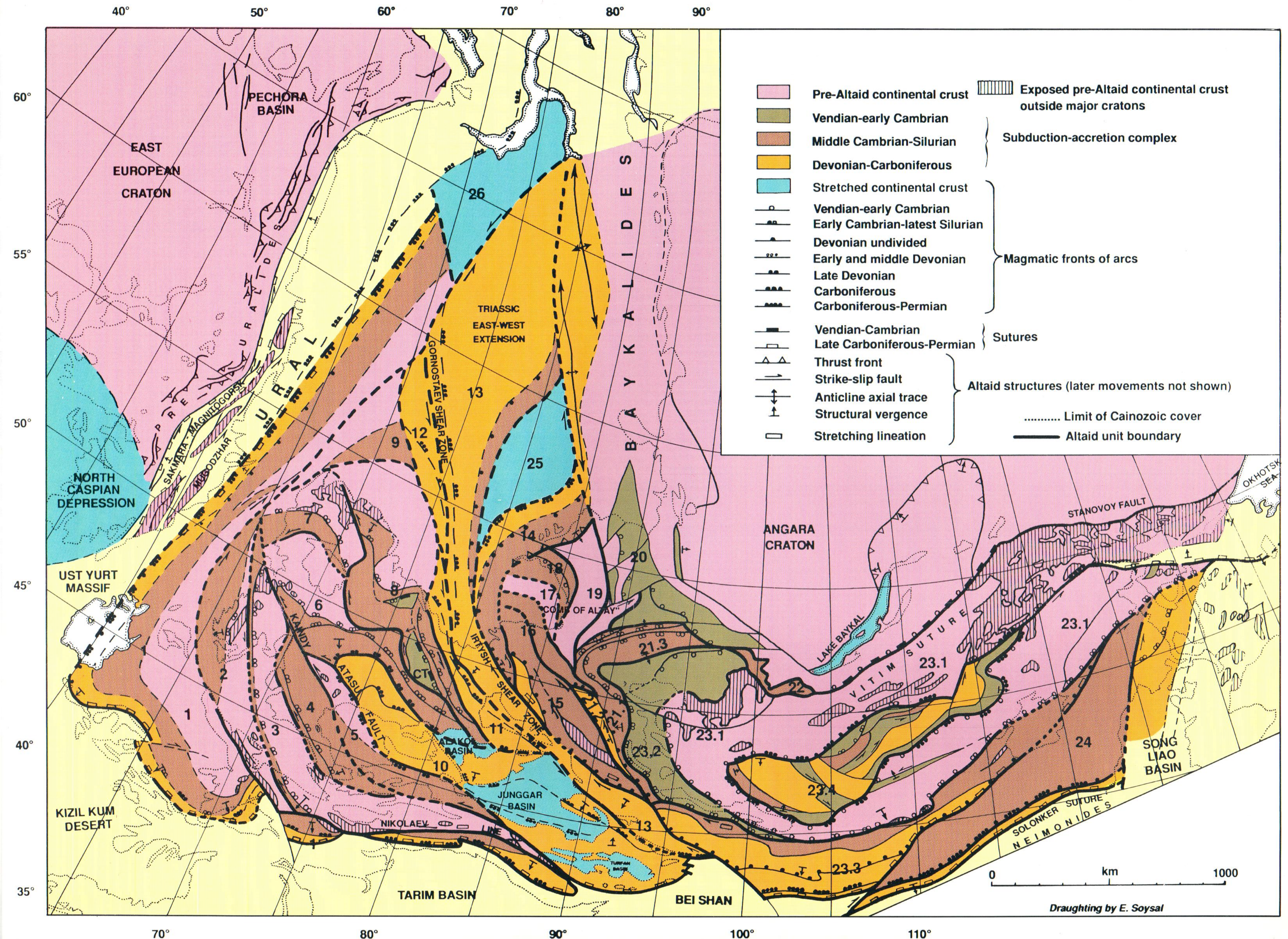
of years[29], and are continuous along subduction fronts[30] (Fig. 2). In our map, we also combine Vendian–Palaeozoic subduction-accretion complexes (only in the extreme east of unit 23.4 is there some Triassic) into a single category, subdivided into three domains according to minimum age of accretion as defined by the age of unconformable forearc sediments and/or intrusive rocks cutting them (Fig. 2). The other domain that we define to help outline the first-order structure consists of pieces of pre-Altaid continental crust. Such pieces invariably turned out to have constituted original arc massifs forming backstops to the accretionary complexes. Within the accretionary complexes, we have noted the accretionary vergence beneath unconformable forearc deposits ('structural vergence' in Fig. 2) and use this as an extra criterion to establish subduction polarity in addition to the facing of magmatic fronts (that is, the direction opposite to the dip direction of subduction zone) and contacts between arc massifs and accretionary wedges.

Steep and laterally persistent, straight or gently curvilinear faults along which entire units are truncated were noted as possible strike-slip boundaries and then searched systematically for offsets. Because some former strike-slip faults turned out to have suffered later significant oroclinal bending and more complicated folding around vertical axes, their identification was an iterative process, proceeding along with palaeotectonic reconstructions.

Regional review

Figure 2 shows the distribution and summarizes the outline stratigraphy and magmatism in the first-order Altaid tectonic units. Most are bounded by large strike-slip faults and many contain a pre-Altaid continental basement of Riphean to locally Vendian

FIG. 2 Generalized tectonic map of the Altaids showing the first-order tectonic units, the pre-Altaid continental fragments, Altaid accretionary complexes and Altaid magmatic fronts. The combined magmatic fronts carry only the symbols representing the earliest and the latest activity. Along the strike-slip faults only the major Altaid displacements are shown, although many of these faults later had motion along them, commonly in an opposite sense; it is these younger motions that are widely mentioned in the literature. Data for structural vergence have been summarized, in addition to the references cited in the text and below, from ref. 64. See Box 1 for a description of the first-order tectonic units. ►



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age, in which pre-Altaid penetrative deformation and metamorphism had ended before the later Vendian. Where data are available, along the large fault boundaries stretching lineations are horizontal and some contain wide mylonite zones, the widest being more than 3 km along the Irtysh shear zone, perhaps the longest-lived strike-slip fault zone in the entire Altaid edifice (Fig. 2, refs 31–33 and B. F. Windley, personal communication), implying very large displacement[34]. The Vendian in the western Altaids (units 1, 2, 5, 7 and 8 in Fig. 2) was a time of rifting characterized by intermediate and mafic volcanic activity, deposition of dominantly non-glaciogenic, mostly marine diamictites and turbidites in rapidly subsiding fault troughs[35–38]. The onset of arc magmatism and subduction-accretion may have progressed generally from east to west within the Altaid collage during the Vendian–Cambrian interval, although evidence for subduction throughout the entire Altaids becomes widespread in the Ordovician. Vendo-Cambrian subduction magmatism and subduction-accretion characterized the margins of units 3, 4, 5, 7, 8, 20, 21.3, 23.1, 23.2, 23.4 and 24. In unit 7 and possibly also in unit 2, it led to ultra-high pressure metamorphism producing metamorphic diamonds and coesite, respectively. The eastern flank of the Kazakhstan orocline is made up of Chingiz-Tarbagatai Vendo-Cambrian tholeiites and Middle Cambrian to Ordovician calc-alkalic volcanics, representing an island arc that originally faced eastward (present geographical orientation)[39] within unit 8 (CT in Fig. 2). This is the only fossil arc in the Altaids whose place of nucleation with respect to the rest of the orogenic system cannot now be surmised.

In the entire Altaids, early Palaeozoic sedimentation outside the pre-Altaid fragments progressed generally from Vendian pelagic ocean floor sediments and distal turbidites through Ordovician and Silurian flysch to Devonian shallow water to terrestrial deposits. After the Devonian, deep water pelagic and flysch sedimentation marched west and south in unit 1, south in unit 3, northeast in unit 5, south and southwest in units 11, 12, 13, 15 and 21.2, northwest in unit 14, and southwest and south in

BOX 1 First-order Altaid units

(1) *Valerianov–Chatkal* (Pre-Altaid continental basement, Altaid accretionary complex and magmatic arc). Pre-Vendian metamorphic basement; Vendian unconformable diamictites forming rift deposits with possible Lower Vendian felsic volcanics; unconformably overlying are Cambrian and Ordovician black slates, limestones and phosphorites; Ordovician to Lower Devonian arc magmatics including both plutons and volcanics; unconformable Middle and Upper Devonian red clastics and Lower Carboniferous limestones; Upper Carboniferous or Permian (locally even possibly Lower Triassic) mainly alkalic felsic magmatism; Ordovician to Devonian fragments of ophiolites, green and bluechists involved in the accretionary complex; uppermost Carboniferous to Lower Permian red clastics overlie the suture to its south and west[65].

(2) *Baykonur–Beshtash* (Pre-Altaid continental fragment, early Palaeozoic accretionary complex and magmatic arc). Riphean metamorphic clastics and volcanics. In the Makbal complex in the south of the unit these contain quartz pseudomorphs after coesite[66] which may be of early Palaeozoic age. Locally overlain unconformably by Vendian marine clastics with mafic and felsic volcanics and diamictites forming rift deposits; Cambrian to Middle Ordovician thick limestones interbedded with cherts and phosphorites resting unconformably on older basement; Middle and Upper Ordovician island arc volcanics, coeval tuffs in intra-arc and forearc basins; Middle and Upper Devonian red clastics are unconformable on all older rocks; Lower to Upper Carboniferous conformable red clastics and limestones[65,67].

(3) *Chu-Terskey* (Pre-Altaid continental fragment, Altaid accretionary complex and magmatic arc). Lower to upper Proterozoic, pre-Vendian metamorphic basement; Vendian-Cambrian ophiolites; Upper Cambrian to Carboniferous are volcanoes and granites; Devonian and Carboniferous clastics in fore- and retro-arc basins; Lower Permian alkaline volcanics and syenites[65].

(4) *Sarytum* (Pre-Altaid continental basement, Altaid accretionary complex and magmatic arc). Proterozoic metamorphic basement; unconformably overlying Middle Cambrian to Silurian arc volcanics; Lower to Middle Cambrian limestones, cherts and phosphorites; Silurian marine clastics; widespread Devonian granites and calc-alkalic volcanics[65].

(5) *Atasu-Mointy* (Pre-Altaid continental basement, Altaid accretionary complex and magmatic arc). Riphean metamorphic basement; unconformably overlying Vendian clastics, diamictites and carbonate rocks forming rift fills; Limestones, cherts and phosphorites in the late Vendian to Middle Ordovician; Late Ordovician to Carboniferous granites and island arc volcanics; Devonian and Carboniferous clastics and limestones; Permian syenites and alkalic volcanics[65].

(6) *Tengiz* (Pre-Altaid continental basement, Altaid accretionary complex, and magmatic arc). Proterozoic metamorphic basement; Vendian marine clastics, cherts and andesites; Ordovician and Silurian flysch and granites; Devonian calc-alkalic volcanics and terrestrial clastics; Carboniferous limestones, coal-bearing deposits, calc-alkalic and alkalic volcanics and granites; Permian alkalic granites and syenites and terrestrial red clastics[65].

(7) *Kalmyk Kol–Kökchetav* (Pre-Altaid continental basement, Altaid accretionary complex and magmatic arc). Proterozoic basement, with latest Riphean or early Vendian bimodal volcanics; Vendian diamictites forming rift fills; early Cambrian ultra-high-pressure rocks including diamonds[68,69]; Lower to Middle Cambrian basalts, andesitic basalts, keratophyres, tuffs, sandstones, cherts and limestones; Lower to Middle Ordovician slates and cherts with intercalated basalts Upper Ordovician conglomerates, sandstones, dacites, andesites and andesitic basalts; Devonian red conglomerates, sandstones, andesites, tuffs and granites; Middle Devonian syenites; Lower Carboniferous limestones and coal-bearing clastics[65].

(8) *Yerementau–Chingiz–Tarbagatai*. Two subunits exist in this unit. One with pre-Altaid continental basement includes the Yerementau fragment and the attached accertionary complex and the other is a tentatively dated Vendian to Middle Ordovician ensimatic island arc that collided with the former in the middle Ordovician. Yerementau basement consists of Riphean and older metamorphic rocks; Lower to Middle Cambrian ophiolites; Middle Cambrian felsic tuffs, cherts, slates; Ordovician andesites and basalts, cherts with intercalated basalts and marine clastics; Silurian varicoloured sandstones and siltstones; Late Ordovician granites; Silurian alkalic granites and syenites; Lower Devonian red clastics and magmatic arc volcanics; Middle and Upper Devonian red clastics; Uppermost Devonian and Lower Carboniferous limestones and flyschoid deposits; Middle Carboniferous red clastics [65,70]. CT is the Vendo-Cambrian, now east-facing Chingiz-Tarbagatai island arc.

(9) *Ishim* (Pre-Altaid continental basement, Altaid arc, Altaid accretionary complex) high-grade Precambrian metamorphic rocks, intruded by both early and late Palaeozoic granites; Ordovician sandstones, slates, cherts and schists of unknown age, unconformably underlying simply deformed Devonian and younger sedimentary and rare volcanic rocks[71].

(10) *Junggaro–Balkhash* (Altaid accretionary complex and arc). Upper Cambrian–Ordovician ophiolites; Silurian sandstones and cherty slates; Devonian to Permian clastics, limestones and arc volcanics with granites[65,72].

(11) *Zharma–Saur* (Magmatic arc and accretionary complex). Ordovician to Devonian ophiolites; Middle Devonian to Carboniferous island arc volcanics tectonically juxtaposed against marine clastic rocks of the same age; Carboniferous and Permian granitoids[6].

(12) *Tar–Muromtsev* (Magmatic arc and accretionary wedge: displaced fragment of 11)[71].

(13) *Surgut* (Accretionary wedge overlain by volcanic arc). Most of this is concealed under the West Siberian basin. Extreme southeastern part (Kalba–Narym region): ophiolites, serpentinitic mélange, debris flow deposits, high-pressure/low-temperature schists (545–470 Myr), Lower Silurian to Upper Devonian cherty deep-water carbonate rocks, Middle–Upper Devonian cherts, Upper Devonian to Lower Carboniferous reef limestones and turbidites; main unconformity at the base of the Middle Carboniferous; Upper Devonian to Upper Carboniferous island arc volcanics; intruded by Permian granites. Much enlarged by Triassic east–west stretching[6,32].

(14) *Kolyvan–Rudny Altay* (Accretionary wedge and volcanic arc). In the extreme south (Rudny Altay) Middle–Upper Devonian volcanic arc atop early Palaeozoic clastics and carbonate rocks intruded by Ordovician, Carboniferous and Permian graintoids; to the west and north, these rocks are replaced by Middle Devonian to Carboniferous turbidites; its

unit 23.3. In unit 23.4 alone, sedimentation became younger centripetally away from unit 23.1 (with respect to present geometry). In all cases magmatic fronts followed the march of deep-water trench sedimentation with a temporal lag of up to ~30 Myr, except in units 1 and 3, where both arc magmatism and migration of deep-water sedimentation were interrupted between the Givetian (late middle Devonian) and the Serpukhovian (later Early Carboniferous). Behind the migrating magmatic fronts, neritic limestones and locally even terrestrial red beds were deposited on shelves, where alkalic magmatism became progressively more widespread after the Silurian.

Trench sedimentation and forearc wedge growth was interrupted after the Silurian in units 2, 3, 4 and 5, and their penetrative southwest-facing fabric became fossilized. In units 3, 4 and 5, the Carboniferous and younger trenches faced away from their earlier counterparts and were located along opposite sides of the units.

As other geologists have emphasized (see for example ref. 2), the entire Altaid system underwent continuous orogenic deformation between the Vendian and the Permian. This is suggested by the numerous local unconformities, gradually shifting magmatic and flysch depositional loci, and the great similarity in style of structures and deformation sequences migrating together with the sedimentary and magmatic axes; it contradicts the hitherto popular model of orogenic episodes affecting the entire orogenic system synchronously. Only in the Permian did high-K anatectic magmatism become essentially 'areal' in the Altaid collage, as it began to break up into a mosaic along numerous strike-slip and normal faults and steep thrusts, accompanied by almost entirely terrestrial sedimentation. No Alpine- or Himalayan-type[25] crystalline nappe complexes imbricating pre-existing continental crust nor any Indus- or Arosa-type narrow sutures can be recognized within the Altaid collage. Continental molasse foredeeps were only constructed after the formation of, and in front of, the Ural, Tien Shan and the Solonker sutures[2]. The flexural ramp valley stages of basins of Junggar-type along

northern part in the Kolyvan range is thrust onto the Anuy–Chuya unit in the Permian[6,71].

(15) *Gorny Altay* (Early Palaeozoic accretionary wedge overlain by middle Palaeozoic magmatic arc; farther west in the 'South Altay' middle Palaeozoic accretionary wedge with forearc basin). Vendian-Lower Cambrian ophiolite, HP/LT schists, Middle Cambrian to Lower Ordovician turbidites and debris flows intruded by Ordovician and Devonian granitoids and unconformably overlain by Silurian sandstones, and reef limestones. Later Middle Devonian calc-alkalic volcanics and Upper Devonian non-marine clastics. The 'South Altay' subunit includes Lower Devonian sandstones and shales, Middle Devonian reef limestones, and Middle Devonian-Carboniferous turbidites[31,32,73].

(16) *Anuy–Chuya* (Arc, accretionary complex and forearc basin). Cambrian–Lower Ordovician turbidite and debris flow deposits unconformably overlain by Ordovician and Silurian shallow marine sandstones and reef limestones. Along its southwestern margin Ordovician and Lower Silurian turbidites are conformable with older rocks; Lower and Middle Devonian island arc volcanics, Upper Devonian marine and non-marine clastics; Devonian granites[31,73].

(17) *Barnaul*: Inferred Precambrian block under Mesozoic–Cenozoic deposits[71].

(18) *Salair* (Accretionary complex and volcanic arc). Cambrian ophiolites, sandstone, shale, limestone tectonically juxtaposed against coeval island arc volcanic rocks; unconformably overlying are Ordovician marine clastics and intermediate composition volcanics; Silurian sandstones and reef limestones; Middle Devonian calc-alkalic volcanics; Upper Devonian marine clastic rocks; all are thrust onto Lower Cambrian sedimentary cover of the Tomsk unit [6,31].

(19) *Tomsk* (Pre-Altaid continental fragment). Granitic gneisses, amphibolites, schists and thick Vendian–Lower Cambrian terrigenous and carbonate rocks[6,31].

(20) *Batenev* (Fragments of the Tomsk unit). Vendian–Lower Cambrian terrigenous and carbonate rocks inferred to lie on Tomsk basement fragments now separated by strike-slip faults of pre-Devonian age[73]. To the east of the Batenev units are Vendian–Lower Cambrian ophiolites and island arc magmatic rocks marking a suture between the Tomsk microcontinent and the Angara craton. These rocks are all overlain by the Devonian Minussinsk basins of extensional origin containing Devonian alkalic volcanics[39].

(21) *Kharkhirin–Western Sayan* (Accretionary wedge and volcanic arc). Includes three subunits formed at the western margin of the Tuva–Mongol unit (21.1) *Kharkhirin sensu stricto* (*s.s.*) (Middle Cambrian–Lower Ordovician accretionary wedge). Mainly turbidites; unconformably overlain by Ordovician–Silurian andesites, sandstones, mudstones and limestones deposited in an intra-arc setting behind a front migrated west from the Tuva–Mongol unit. Silurian and Devonian granitoids are stitching plutons between the Kharkhirin and Tuva–Mongol units[32,33]. (21.2) *Delyun–Sagsai* (Accretionary wedge and forearc). Middle and Upper Devonian sandstones, shales, subordinate cherts; considered a fault-separated part of the Kharkhirin *s.s.*[73] (and B. F. Windley, personal communication, 1993). (21.3) *Western Sayan* (Accretionary complex and island arc). Vendian–Lower Cambrian ophiolites, HP/LT schists, ophiolitic mélanges, Cambrian–Silurian turbidites and subordinate cherts, reef limestones; all unconformably overlain by Upper Silurian coarse clastics and intruded by granites[6].

(22) *Oka–Jedinsk* (Volcanic arc and accretionary complex). A fault-bounded wedge of probable Vendian to early Cambrian ophiolites and debris flow deposits, Ordovician–Silurian cherts, flysch, and limestones; possible Cambro–Silurian island-arc volcanic rocks. Both assemblages thrust onto the Tuva–Mongol unit[6,74,75].

(23) *Tuva–Mongol sensu lato* (*s.l.*) This major unit has a number of subunits little displaced with respect to the pre-Altaid continental core of the unit. These subunits are: (23.1) *Tuva–Mongol* s.s. (Vendian–Permian magmatic arc on pre-Altaid continental basement): Early Precambrian to Riphean metamorphic rocks, locally separated along later strike-slip faults by bands of Vendian–Lower Cambrian ophiolites; unconformably overlain by Vendian–Cambrian shelf carbonates; coeval calc-alkalic volcanics frame its margins; early, middle and late Palaeozoic granites, and subordinate Devonian and Permian syenites; middle and late Palaeozoic clastic rocks in diverse types of superimposed basins; Devonian calc-alkalic and abundant Permian calc-alkalic and alkalic volcanics[33,76]. (23.2) *Ozernaya* (Tuva–Mongol magmatic arc which migrated onto an accretionary complex). Vendian–Lower Cambrian ophiolites and ophiolitic mélange; Lower Cambrian clastic rocks, limestones, cherts, debris flow deposits, intruded by Cambrian and Devonian granitoids[31,72,77,78]. (23.3) *South Mongolian* (Accretionary wedge which grew to the south of the Tuva–Mongol s.s. unit from the Ordovician to the early Carboniferous). Ophiolites, Silurian–Devonian cherts, limestones, Ordovician to Lower Carboniferous marine clastic rocks, Upper Silurian to Lower Carboniferous andesites, dacites and rhyolites, Lower Carboniferous debris flow deposits; Devonian reef limestones unconformable on lower Palaeozoic sandstones and shales; all of the above were imbricated with south vergence and age of calc-alkalic volcanics become younger in the same direction; all of the above are unconformably overlain by mid-Carboniferous to Permian volcanic and sedimentary rocks[79–81]. (23.4) *Khangai–Khantey* (Accretionary wedge and magmatic arc). Vendian–Lower Cambrian ophiolites, Lower Palaeozoic to Carboniferous turbidites, mafic and intermediate volcanic rocks, tuffs, subordinate cherts; all of the above were intruded by Permian, Triassic and Jurassic granitic rocks [33].

(24) *South Gobi* (Magmatic arc on pre-Altaid continental basement). Precambrian granitic gneisses, Riphean to Lower Cambrian clastic and calc-alkalic volcanic rocks, Ordovician to Lower Devonian turbidites, Lower Devonian calc-alkalic volcanics ranging from andesites to rhyolites; early Palaeozoic granites; along its southern rim Carboniferous flysch with southerly imbrication; all unconformably overlain by Upper Carboniferous and Permian calc-alkalic volcanics[82–84].

(25) *Nurol* (Permo-Mesozoic basin overlying stretched continental crust). Silurian to Middle Carboniferous deformed marine clastic and carbonate rocks intruded by late Palaeozoic alkalic basaltic sills and dykes. Total thickness of crust is reduced to 36 km (refs 49, 71) compared with more than 40 km in surrounding areas.

(26) *Nadim* (Permo-Mesozoic basin overlying stretched continental crust). One of the deepest parts of the West Siberian basin, similar to the Nurol basin[49,71].

the southern Altaids originated only after the onset of Cimmeride collisions to the south in the late Triassic[40].

Tectonic evolution

In the following description, all orientations refer to the reconstructed geographies shown in Fig. 3. The most important constraint for the initial conditions of the Altaid evolution is the interpretation that Baltica (Vendian–Palaeozoic nuclear Europe including the east European craton) and Siberia (Vendian–Palaeozoic nuclear Asia including the Angara craton) may have been attached to one another along their present northern boundaries during the Vendian. Palaeomagnetic data[41,42] allow us to place the two cratons as shown in Fig. 3A. Late Vendian rifting between Baltica and Siberia is indicated on the European margin by the 600-Myr dykes in both Finnmark[43] and the northern Kola Peninsula[44], and by extensive Vendian diamictite deposition and volcanism in tectonically active basins[45]. Their Siberian counterpart may be located in the poorly dated (possibly latest Riphean–Vendian) rift fills of the Taymyr peninsula, whose ages have recently been revised to become younger and thus closer to the European rocks[5].

The combined Baltica/Siberia had what appears to have been an active eastern margin underlain by the Riphean/Vendian pre-Uralide collisional orogen to the east of Baltica[46] and by the Baykalide collisional orogen to the east and north of the Angaran craton of Siberia[5]. The Baykalide collision of the Tuva-Mongol (unity 23.1), Tomsk (unit 19) and Barnaul (unit 17) microcontinents with the Angara craton may in fact have triggered the subduction outboard of the collided fragments, although to the east and northeast of unit 23.1 Vendian subduction continued into the Palaeozoic, directly linking the Baykalide and Altaid evolution.

Already during the Vendian, segments of this marginal orogen began to rift from the combined Baltica/Siberia. Active rifting is documented in units 1, 2, 3, 5 and 7. The conjugte Baltica/Siberia margin contains similar evidence in the Northern Ural[5,47]. In addition, a line of 'Riphean to Palaeozoic rifts' with Vendian–Cambrian fill characterizes the present western boundary of the Baykalides in the basement of the west Siberian basin[48,49]. This rifting event occurred later southwards towards the present-day southern Ural, where it occurred at the Cambro-Ordovician transition[6].

We term the fragment thus rifted off Baltica/Siberia the Kipchak arc, after the former aboriginal language group spoken in the area where its fragments are now found. Until the Devonian it bowed away from the two cratons with a 'free end' possibly attached to a transform fault at its southern terminus (Fig. 3B), while at its northern end it probably remained attached or close to Siberia, where the early Palaeozoic accretionary complex in units 8, 15 and 16 is larger than in other parts of the arc (Fig. 3B). The accretionary complex of the Kipchak arc became progressively smaller towards the southwest away from its main source in Siberia and may have resembled the present Aleutian accretionary complex[50]. The ocean that opened behind the Kipchak Arc is herein called the Khanty–Mansi ocean after the aboriginal population of northern West Siberian lowlands. At this time the Sakmara/Magnitogorsk marginal sea in the southern Urals was expanding, possibly behind the migrating Mugodzhar arc[51].

By early Devonian time (Fig. 3C), growth of subduction-accretion complexes in front of units 1–5, ceased. We interpret this as their being laterally stacked along their bounding strike-slip faults as shown in Fig. 3C. The cause of this strike-slip stacking may have been the collision of the southern end of the Kipchak arc with the Mugodzhar arc in the southern Ural, as suggested by the sudden influx there of thick Early Devonian clastics and a concurrent drop in subduction-related magmatism[51]. A Devonian subduction-accretion wedge, by contrast, began growing to the north of units, 6, 7 and 8, and the Devonian magmatic front migrating onto them turned them into new 'arc massifs' (Fig. 2).

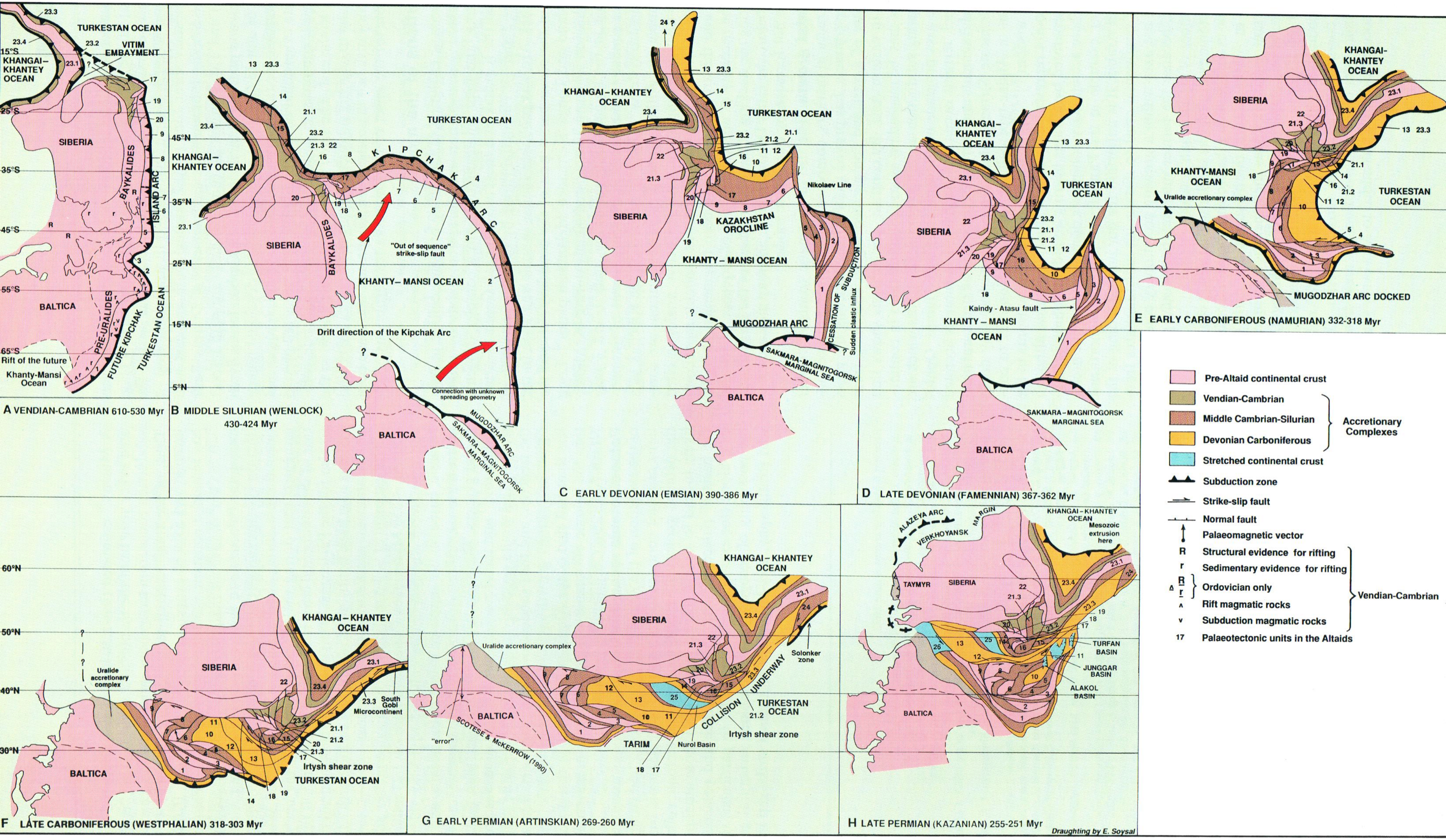
Oblique southwesterly subduction at this time was going on all along southern Mongolia and the Altay mountains. The oceanic Vitim embayment (Fig. 3A and B), lined by the western Sayan arc (unit 21.3), had closed by tightening of the gulf and had pinched the western Sayan arc by the Late Silurian (Fig. 3B and C). This tightening was probably accomplished by an eastward motion of unit 23.1 that entrained the ophiolites associated with the western Sayan arc along it and gave rise to the Oka–Jedinsk zone (unit 22; Fig. 3C). The Anuy–Chuya fragment (unit 16) of Cambro–Ordovician accretionary complex bypassed the western Sayan pinching and was emplaced against the Barnaul unit (number 17) by right-lateral strike-slip faulting. This led to further strike-slip stacking within the 'Comb of Altay' (Fig. 2) and generated the alkalic volcanism in the Minusinssk basins[31].

By late Devonian time (Fig. 3D), the present apex of the Kazakhstan orocline had moved left-laterally along the Kaindy Atasu fault (see Fig. 2) relative to its present southwestern flank, leading to arc magmatism along the present northeastern front of the Atusu–Mointy fragment (unit 5). It may also have begun to be internally disrupted by strike-slip faults (now) parallel with the Kaindy Atasu fault, as suggested by the Middle Devonian alkaline intrusives at least along the boundary between the future units 7 and 8 (ref. 52) (Fig. 2). By this time, a substantial subduction-accretion complex had grown inside the Kazakhstan orocline, into which the magmatic front migrated (Fig. 2). Within the older subduction-accretion complex, across which the magmatic front had moved, the intrusion of high-K granites in the retroarc area and the deposition of shallow water sedimentary rocks in the forearc region suggest that a continental crust of near-normal thickness was most probably generated here by subduction-accretion and arc magmatism[26].

In the Early Carboniferous (Fig. 3E), the approach of Baltica to Siberia at the expense of the intervening Sakmara–Magnitogorsk, Khanty–Mansi and the Turkestanian oceans led to transpressional slip of the tip to the Kipchak arc to the north and caused subduction to resume under the segment now represented by units 1 and 2. Ongoing oblique subduction along southern Mongolia and the Altay emplaced the Gorny Altay (unit 15) against the Delyun–Saksai Devonian accretionary wedge (unit 21.2) and thus terminated its growth. By this time the apex of the Kazakhstan orocline had probably begun tightening by extensive internal strike-slip faulting separating the Tengiz, Kalmyk Kol–Kökchetav and the Yerementau–Chingiz–Tarbagatai (units 6, 7 and 8, respectively) from one another, because the faults separating these fragments all affect Carboniferous rocks (some with later smaller right-lateral slip owing to north–south shortening[53], not shown in Fig. 3).

By late Carboniferous time, Baltica had begun shearing with respect to Siberia in a right-lateral sense (Fig. 3F). This shear was combined with convergence and thus both tightened the entire Kazakhstan orocline plus unit 1 and transported it westward with respect to Siberia, this continuing the right-lateral shear along the Altay–South Mongolian area. Both the Rudny Altay–Kolyvan unit (14) and the combined Zharma–Saur, Tar–Muromtsev, Surgut units (11, 12 and 13, respectively) moved west with respect to the 'Comb of Altay'. This movement continued into the Early Permian (Fig. 3G) pulling apart the Nurol basin (unit 25) and leading to alkaline magmatism in its basement.

FIG. 3 Schematic and simplified palaeotectonic sketch maps showing the evolution of the Altaids. Positions of continents were modified from refs 20, 41, 42. Palaeomagnetic vectors shown were averaged from determinations 08080, 08081, 08082 and 08110 in ref. 85. In G the ±10° 'error' is with respect to the position given in ref. 20 and may have resulted from shortening in the Urals, shortening in Kazakhstan or palaeomagnetic measurement error. ►


A VENDIAN-CAMBRIAN 610-530 Myr
B MIDDLE SILURIAN (WENLOCK) 430-424 Myr
C EARLY DEVONIAN (EMSIAN) 390-386 Myr
D LATE DEVONIAN (FAMENNIAN) 367-362 Myr
E EARLY CARBONIFEROUS (NAMURIAN) 332-318 Myr
F LATE CARBONIFEROUS (WESTPHALIAN) 318-303 Myr
G EARLY PERMIAN (ARTINSKIAN) 269-260 Myr
H LATE PERMIAN (KAZANIAN) 255-251 Myr
TURKESTAN OCEAN
VITIM EMBAYMENT
KHANGAI–KHANTEY OCEAN
SIBERIA
BAYKALIDES
ISLAND ARC
BALTICA
PRE-URALIDES
FUTURE KIPCHAK
Rift of the future Khanty-Mansi Ocean
KIPCHAK ARC
"Out of sequence" strike-slip fault
KHANTY–MANSI OCEAN
Drift direction of the Kipchak Arc
Connection with unknown spreading geometry
MUGODZHAR ARC
SAKMARA–MAGNITOGORSK MARGINAL SEA
KAZAKHSTAN OROCLINE
Nikolaev Line
CESSATION OF SUBDUCTION
Sudden clastic influx
Kaindy - Atasu fault
Uralide accretionary complex
MUGODZHAR ARC DOCKED
South Gobi Microcontinent
Irtysh shear zone
"error"
SCOTESE & McKERROW (1990)
TARIM
Nurol Basin
COLLISION
UNDERWAY
Solonker zone
ALAZEYA ARC
VERKHOYANSK MARGIN
TAYMYR
Mesozoic extrusion here
TURFAN BASIN
JUNGGAR BASIN
ALAKOL BASIN
15°S
25°S
35°S
45°S
55°S
65°S
45°N
35°N
25°N
15°N
5°N
60°N
50°N
40°N
30°N
Pre-Altaid continental crust
Vendian-Cambrian
Middle Cambrian-Silurian
Devonian Carboniferous
Accretionary Complexes
Stretched continental crust
Subduction zone
Strike-slip fault
Normal fault
Palaeomagnetic vector
R Structural evidence for rifting
r Sedimentary evidence for rifting
Ordovician only
Rift magmatic rocks
Subduction magmatic rocks
Vendian-Cambrian
17 Palaeotectonic units in the Altaids
Draughting by E. Soysal

The last act of the Altaid evolution during the Palaeozoic was a reversal of the shear sense between Baltica and Siberia (Fig. 3H). This reversal was accompanied by extension across the future west Siberian basin as Baltica and its appendage west of the Gornostaev shear zone (Fig. 2) swung south and east with respect to Siberia. It brought the arc fragments of Zharma–Saur (unit 11) and Tar–Muromtsev (unit 12) eastward with respect to Siberia, and juxtaposed them against the Carboniferous flysch deposits of unit 13 (ref. 6). A part of this transtensional regime was responsible for rifting open the Nadim, Alakol, Junggar and the Turfan extensional basins, before the latter three fell prey to late Triassic compression resulting from the Cimmeride collisions far to the east. The same kinematics led to collision in the Taymyr and to ongoing subduction along the Alazeya arc behind the Verkhoyansk belt in northeastern Siberia and may have been responsible for the onset of the Tunguska trap eruptions.

Implications of the model

The Palaeozoic evolution of the Altaid orogenic collage in Asia records the origin, evolution and disruption mainly by strike-slip faulting, and final amalgamation into a complex orogenic collage, of the Kipchak and the Tuva–Mongol/Comb of Altay arcs (Figs 2 and 3). The initial rifting by back-arc spreading of the Kipchak Arc was probably similar in scale and style to the opening of the ocean basins west of the boundary between the New Zealand and Tonga–Kermadec–Melanesian plates[54]. Long non-subduction segments that existed mainly during the Middle Palaeozoic in the segment represented by units 1 and 3 may have been similar to the north Fiji basin segment of the peri-Australian arc systems[55]. Our Fig. 3B depicts the Kipchak as a single, simple arc. Although the present observations are compatible with this, comparison with the active analogue cited above suggests that the tectonic picture was probably more complicated, and the arc may well have been fragmented along its strike. The necessity of introducing 'out-of-sequence' strike-slip faults during the stacking of the western flank of the Kazakhstan orocline before the Early Devonian (Fig. 3B) may indicate complications not foreseen by our simple model.

Continental growth. The use of magmatic fronts of former arcs as structural markers, combined with arc massif/accretionary wedge contacts, has proved fruitful in deciphering the gross architecture of a vast and complicated region stretching from the Ural to eastern Asia. By contrast, our analysis shows that ophiolites may be misleading as structural markers in continuously growing subduction-accretion complexes across which arc magmatic axes prograde oceanwards in episodic jumps. Ophiolites in such terrains occur in a haphazard fashion as accreted slivers and fragments and carry no significance as structural markers to delineate former palaeotectonic entities as they do in Himalayan or Alpine-type collision orogens. Contrary to conventional wisdom[18,19,21,56–58], discrete arc magmatic fronts in the Altaids do not represent former individual island arcs, although they are separated by terrains bearing abundant ophiolitic fragments. Where accretionary complexes dominate orogenic architecture, for example in the Pan-African terrains of northeast Africa and Arabia, it is important for our understanding of the growth of continental crust to distinguish individual arcs from migrating arc axes within a growing accretionary complex of a single arc, because the former interpretation would produce a larger number of sutures than actually exists.

This tectonic evolution was similar to that which characterized the tectonic evolution along the North American Cordillera, and especially in Alaska, during the Mesozoic and early Cenozoic. An important aspect of it was the generation of immense subduction-accretion complexes along the Tuva–Mongol/Comb of Altay and the Kipchak arc front. The total area now occupied by these complexes within the Altaids is some 5.3 million km^2, or about one-ninth of the entire surface of Asia. During the $\sim$350 million years of Altaid evolution, an area slightly larger than two soccer fields thus was added to Asia every year. Howell & Murray[59] estimated that 1.30 km^3 of sialic material is generated every year from the mantle and some 1.70 km^3 is fed into subduction zones from terrigenous, pelagic and biogenic sources. Thus, of the total accreted to the continents, about 45% is of juvenile and 55% of exogenically recycled sources. If this ratio has remained constant since the beginning of the Phanerozoic, $\sim$0.205 km^3 of juvenile material must have been added annually during the Palaeozoic to the continental crust along Altaid subduction systems supporting models of significant growth of continental crust during the Phanerozoic[60]. Dewey and Windley[61] estimated that during the Mesozoic–Cenozoic, the net growth rate of the continental crust has been 0.429 km^3 yr^{-1}. If this were so also for the Palaeozoic, it suggests that the Altaid subduction systems may have contributed nearly 48% of the Earth's total of new continental crust during the Palaeozoic.

Our estimate of $\sim$2.5 million km^2 of juvenile matter added to Asia in $\sim$350 Myr makes Coney's[62] figure of 7.23 million km^2 added to North America during only 165 Myr since the middle Jurassic, based on the supposed extent of the oceanic and juvenile arc material, rather surprising. Owing to the absence of continental glaciers, Mesozoic sea level was higher than that in the Palaeozoic[63] and therefore continental denudation was probably slower. This would probably have made the turbidite input into the trenches, and thus subduction-accretion slower. The alleged significantly larger growth rate of North America in a time span less than half that of the Altaid evolution might therefore imply that the volume of oceanic subduction-accretion material in the North American Cordillera was overestimated.

Palaeotectonic reconstructions. Finally, our reconstruction of the evolution of the Altaid collage has shown that reconstructions of major continental units during the Palaeozoic based on the detailed geological structure of present tectonic collages is likely to lead to a more refined picture than those attempted on the basis of palaeomagnetic, biogeographic and palaeoclimate data alone (for example, refs 20 and 41). In particular, there is the possibility of recognizing, by combined structural geology and stratigraphy, very-large-scale latitudinal strike-slip motion. □

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