On Terrane Analysis [and Discussion]

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On terrane analysis

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Many recent papers on displaced crustal masses are organized around 'terranes' given only geographic names, and are bewildering for other than local experts; self-explanatory descriptive or genetic terms should be incorporated in most designations. Plate-tectonic interpretations of aggregated terranes that incorporate awareness of how modern arc systems vary and evolve contain implicit and testable predictions, but too many interpretations are based instead on invalid assumptions. As actualistic models are applied to analyses of orogenic belts, much more mobilistic interpretations than those generally now visualized will probably emerge. An example is made of the Carpathian region.

1. Introduction

Most orogenic belts contain as important components the sweepings from subducted oceanic plates and the variably aggregated and deformed light crustal masses brought together as plates converged by subduction of intervening oceanic lithosphere. Many belts further display disruption by strike–slip faulting. The characterization of rock assemblages juxtaposed by such processes, and the evaluation of palaeomagnetic, palaeontologic, and palaeoenvironmental evidence for motion histories, are critical steps in deciphering the evolution of orogenic belts. Much additional understanding of orogenic belts can come from the seeking of plate-tectonic relationships between components.

2. Terrane nomenclature

All orogenic belts contain tracts that have been transported long distances relative to adjacent tracts from which they are now separated by sutures or major faults. Coney *et al.* (1980) proposed that such tracts be termed 'terranes', and the term has become popular (see, for example, Howell *et al.* 1985; Howell 1989) for known ('allochthonous', 'displaced', or 'exotic' terranes) or possible ('suspect' terranes) transported masses. The term often is given as 'tectonostratigraphic terrane'. Different geologists have formally named terranes as diverse as out-of-place continental masses or island arcs, or lithologic units therein; entire accretionary wedges, or contrasted melange assemblages, or isolated slices of coherent material in wedges; displaced bits in strike–slip régimes; adjacent thrust sheets in foreland thrust belts; components within crystalline complexes that might be bounded by faults; and concordant metavolcanic and metasedimentary packages in the walls of a pluton.

The best place to see how the term terrane is used is in the volume edited by Howell (1985), wherein most authors apply it to lithologic or tectonic units which might have been juxtaposed by plate motions. One group of authors designates terranes with geographic names and organizes descriptions around these. Ji & Coney (1985) split China into 33 'fault bounded' terranes and schematize the speculative Phanerozoic history of each with a column of lithology and age. Most of these terranes are inferred to be continental fragments; ages of collisions are asserted for all terranes, although few sutures are known, few bounding structures are characterized, and some boundaries are merely basin onlaps. More soundly based, but similarly organized around geographically named terranes, are five papers (Blake *et al.* 1985*a*, *b*; Hill 1985; Irwin 1985; Mortimer 1985) in the volume dealing with the Klamath Mountains region of California and Oregon. These papers collectively name 28 terranes and subterranes, plus numerous additional 'belts', all without qualifying nouns or adjectives regarding age, lithology, structure, or tectonic setting. Descriptions are keyed to these memory-defeating abstract names. Despite the obvious relevance for plate-tectonic analysis of the melanges, island arcs, and ophiolites hidden in the nomenclature of these Klamath classifiers, none of the five papers attempts plate-tectonic synthesis. None tries to pair accretionary wedges to magmatic arcs, or to define polarities of subduction, or to evaluate whether sutured arcs were accreted separately to the continent or were aggregated first into composite island arcs. Only a few units and structures are even assigned vague plate-tectonic contexts with single phrases or sentences. There are mentions of palaeomagnetic and palaeontologic evidence for plate motions but no analyses of how these were accommodated.

By contrast, one paper (Harper *et al.* 1985) in the Howell volume presents a plate-tectonic synthesis of the Klamath region, and instead of terrane terminology, it uses an easily understood, descriptive terminology, in part genetic, for the components of the complexly sutured aggregate. Other authors in the volume who present plate-tectonic syntheses for other regions and who either eschew terrane terminology in favour of descriptive nomenclature or add descriptive modifiers to terrane terms include Box (1985), Ernst *et al.* (1985), Hawkins *et al.* (1985), Kimbrough (1985), and McCabe *et al.* (1985).

These and other recent papers display a tendency for investigators of displaced crustal masses to place themselves in one of two contrasted groups. Most of those who favour geographic terrane nomenclature espouse objective description and classification and largely neglect genetic relationships between assemblages; predictions are not made and hence few tests are applied. Most members of the opposed descriptive-nomenclature group use models of genetic relationships and advance plate-tectonic interpretations through self-explanatory terminology. Predictions implicit in the model-driven classifications can be tested, which permits rejection of inappropriate models.

It appears that the proportion of researchers who understand the empirical behaviour and relationships of components of modern plate-interaction systems is much higher in the descriptive-terminology group than in the geographic-terminology one. Such understanding is not easily obtained, for not only does no textbook contain it, but most of the casual treatments of plate-boundary systems that do appear in textbooks incorporate false assumptions. Even the new book by Howell (1989) lacks understanding both of subduction and of triple junctions. My harsh inference is that members of the geographic-terminology group do not present the critical evidence needed for evaluating plate interactions because they generally do not comprehend how plates interact.

Howell (1989) argued that doubts as to the reality of additional terranes should be resolved by naming all possible ones, reserving for later investigators the task of determining whether or not adjacent terranes have been juxtaposed across major structures. Application of this philosophy will not only clutter the literature but, worse, will inevitably lead to circular rationales justifying the initial discriminations. Indeed, much foolish speculation already has come from the practice, in northern Alaska and southern California, for example.

The following section notes some of the features of modern plate systems that should be taken into account when progressing from classification to comprehension of ancient orogenic belts. Few geologists working with orogenic belts comprehend actualistic plate tectonics.

3. Actualistic plate tectonics

Plate tectonics has given us the framework within which to perceive relationships between tectonic and magmatic features and movement histories. Conversely, plate-tectonic interpretations carry implicit predictions that can be tested against other data. Much of the crustal material in orogenic belts has been tectonically accreted by processes related to subduction. Such material was conveyor-belted atop plates of oceanic lithosphere toward subduction zones, at which some materials disappeared beneath overriding plates whereas others, variably dismembered, were scraped off against them. Such accretion can take place against an island arc or an Andean-type continental margin, or between colliding arcs. As overriding continental plates are themselves moving, with their bounding subduction systems, and as island arcs migrate, reverse polarity, and collide with each other and with continents or lesser crustal masses, histories and characteristics of accreted orogenic complexes commonly vary greatly along strike. Accreted materials can have moved 10000 km relative to the continent against which they are emplaced; or they may be rifted away a mere 100 km, then collapsed back by subduction. Sedimentation in trenches is mostly by turbidites flowing along the trenches, rather than by sediments moving directly into trenches from adjacent arc sectors, and terrigenous sediments can have sluiced 3000 km from their sources before being imbricated into an accretionary wedge.

Seven very large lithospheric plates, and numerous mid- and small-sized ones (the concept of coherent plates breaks down at the small-scale end), are now all moving relative to all others. Corollaries are that all plate boundaries are also moving, and that most change greatly in length and shape as they move. Parts of many plates undergo severe internal deformation, and boundaries often jump or migrate to new positions. Relative velocities between adjacent plates presently range up to about 15 cm a^{-1}.

Arc systems develop where oceanic plates sink beneath overriding plates that can be continental, transitional, or oceanic. Many individual arcs are continuous across the diverse crustal types. Arcs commonly are inaugurated by subduction reversals consequent on collisions between other arcs and light crustal masses, and collision histories vary greatly along trend. Oceanic arcs migrate and lengthen with time, and one sector of a continuous arc can have been inaugurated tens of millions of years later than another sector, or after another sector has collided and stopped. Petrologic and crustal features evolve as activity continues in a given sector. I discussed and referenced such features in recent papers (Hamilton 1988, 1989) and documented many of them in a monograph (Hamilton 1979).

'Absolute' velocities of present large plates – their relative velocities in an approximate zero-sum frame – correlate positively with the lengths of ridges and of trenches along their perimeters, and negatively with the proportion of continental lithosphere within them (Carlson 1981). Plates are propelled primarily by gravitational forces, and on average pull by the descending slab is about 2.5 times as important in moving plates as is slide of plates away from ridges, whereas thick continental lithosphere retards motion by drag (Carlson 1981). Subduction-pull increases with density and thickness, and hence with age, of subducting lithosphere, and forward velocities of subducting plates, roll-back velocities of trench hinges, and extension or drag of overriding plates vary correspondingly (Hilde & Uyeda 1983; Jarrard 1986; Jurdy & Stefanick 1988). The 80 or 100 km of relief of the base of an oceanic plate, between lithosphere and less-dense asthenosphere, is much more important in producing ridge-slide than is the 3 or 4 km of bathymetric relief of the top of the plate. Major plate motions are controlled primarily by large lateral variations in lithosphere density and thickness that result primarily from cooling (Carlson 1981; Hager & O'Connell 1981).

Much published tectonic speculation and geophysical modelling incorporates the false assumptions that subducting plates roll over hinges, and slide down slots, that are fixed in the mantle, and that overriding plates commonly are shortened compressively. Rather, hinges commonly retreat – roll back – into incoming oceanic plates as overriding plates advance, even though at least most subducting plates are also advancing in 'absolute' motion. Subducting slabs sink more steeply than the inclinations of Benioff seismic zones, which mark positions, not trajectories, of slabs. Perhaps the most obvious evidence for roll-back is that the Pacific Ocean is becoming smaller with time, but much other evidence has been presented by many authors. The typical régime in an overriding plate above a sinking slab is one of extension, not shortening (although of course great shear and shortening affect the accretionary wedge in front of the overriding plate). A corollary, often overlooked in palinspastic analyses, is that subduction can occur beneath only one side at a time of an internally rigid plate.

As island arcs migrate oceanward over subducting plates, marginal basins of new oceanic lithosphere open behind the arcs (Taylor & Karner 1983). Some migration is accomplished by the splitting of a magmatic arc and the migration of its forward half away from the rear half, and some by irregular sea-floor spreading behind the entire arc. The magmatic welt can move forward with the advancing part of the overriding plate, can be abandoned as a remnant arc on the rear plate, or can be split between them. Oceanic island arcs do not bound rigid plates of old lithosphere, but instead mark the fronts of plates of young lithosphere that are widening in the extensional régimes above sinking slabs.

Arcs increase in curvature as they migrate. A migrating arc becomes pinned where it encounters thick crust in the subducting plate that either is non-subductible or that forms a stiffening girder, and festoons and sharply curving arcs result where migration continues away from such obstructions.

An island arc is not a feature fixed on an overriding plate, but rather is a belt of arc-magmatic rocks formed above that part of a subducting slab whose top is 100 km or so deep. The belt migrates, with or without the part of the overriding plate on which it stands, to track that contour as the slab falls away. Although much oceanic back-arc-basin lithosphere forms by regular or irregular spreading behind an arc, much also may form by the rapid migration of a magmatic arc which forms a sheet of arc crust rather than forming a full island-arc welt. On-land ophiolites are sections of upper oceanic lithosphere that probably are dominated by these two types of back-arc basin materials rather than by the products of spreading mid-ocean ridges.

There appear to be two major processes of emplacement of ophiolites within orogenic belts. One is in the collision of an advancing arc with a continent or other island arc, the thin ophiolitic leading edge of the overriding plate ramping onto thick-crustal parts of subducting plates. Such thrusting is in the sense of subduction. (The hypothetical process of 'obduction', whereby a sheet of oceanic lithosphere is split from a subducting slab and shoved, in the opposite sense of thrusting, atop the thick crust of an overriding island-arc or continental plate, is invoked by many writers, but the process defies mechanical analysis and has yet to be proved to have operated anywhere. Confusion is introduced by writers who misuse the term 'obduction' to imply onramping in the sense of subduction, which does happen but is opposite to the original definition of the term.)

The second major process of ophiolite emplacement is a common byproduct of collision of an arc with a continent or another arc. A new subduction system of opposite dip breaks through behind the collided arc and leaves attached to it a strip of back-arc basin crust that becomes raised as accretionary-wedge materials are stuffed beneath it. Such an ophiolitic strip may remain at the leading edge of a plate as long as subduction continues beneath it, subject to tectonic erosion, but it will become part of a suture system when another non-subductible crustal mass collides with it. Oceanic arcs commonly are not inaugurated by the breaking of subduction through old oceanic crust, but rather break through near boundaries between thin and thick crust and migrate over the plates of thin crust (Hamilton 1979, 1988; Karig 1982).

4. Palaeotectonic analysis

The evaluation of ancient tectonic systems in terms of terranes and actualistic plate tectonics has barely begun. Shortcomings of terrane analysis were noted earlier, and on the other hand too many published analyses of orogenic belts, although purportedly plate-tectonic, are made without understanding of plate behaviour. The success of the plate-tectonic paradigm has produced a complacency that has cluttered the geologic literature with speculations based on invalid models and devoid of testable predictions.

The central European belt of complex late Mesozoic and Cenozoic terrane accretion has been intensively studied by generations of geoscientists yet still is understood only poorly. Interpretations continue to vary widely but have tended to evolve from geosynclinal toward plate-tectonic concepts. The general view is that the region records the slow opening and closing of small ocean basins and the accompanying collisions of crustal fragments, but all details are disputed. Recent analyses range from modest modifications of stabilist theory (Debelmas 1989; Foldvary 1988; Sandulescu 1988), wherein slow subduction of small oceanic basins is added to classical Alpine overthrusting explanations, to sophisticated interpretations that incorporate actualistic plate tectonics (Dewey *et al.* 1989; Gealey 1988).

I view Europe from the perspective of Indonesian and western Pacific analogues (Hamilton 1989) and regard even the most mobilistic of the modern interpretations of Alpine Europe as likely too conservative. If those analogues are indeed appropriate for evaluating the broad and complex Tethyan region of Mesozoic and Cenozoic rifting and plate convergence, then Alpine Europe may record the subduction of much more oceanic lithosphere than is commonly assumed. Too little attempt has yet been made to pair accretionary wedges to magmatic arcs, or to match palaeobiogeographic and sedimentological data to rifting and drifting histories, or to entertain complexities like those now known to operate in Pacific arcs.

Within central Europe, my own familiarity is greatest with the Carpathian system, where the distribution of late Mesozoic and Cenozoic accretionary-wedge materials, magmatic-arc igneous rocks, and other plate-interaction features lead me to a far more mobilistic view than is held by most regional experts. (My familiarity comes partly from the literature, and partly from extensive field-tripping in Slovakia, organized by Čestmír Tomek and led by regional experts, and from access to unpublished data and discussions with many geoscientists on a visit to Hungary coordinated by György Pogácsás.) My analysis shares much more with the early plate-tectonic papers by Bleahu *et al.* (1973) and Szadeczky-Kardoss (1973) than with most more recent syntheses of the regional geology (Burchfiel 1976; Csaszar *et al.* 1987; Foldvary 1988; Kazmer & Kovacs 1985; Royden & Baldi 1988; Sandulescu 1988; Unrug 1984).

As most observers agree, the Carpathian arc apparently is a response to the tectonic filling of what was in early Tertiary time a westward-opening oceanic embayment. The presently dominant explanations for the tectonic filling (Balla 1986; Royden & Baldi 1988; Royden & Burchfiel 1989) visualize the jamming ('escape tectonics') of a previously coherent continental plate, pushed obliquely from behind by north-moving plates and bounded and sliced by strike–slip faults as needed to fit, into this embayment. My contrary inference that the dominant processes were the migration of an arc (for the Carpathian arc itself) and the complex suturing of various plates, some of them far-travelled (for the inner Carpathians and intra-Carpathian region), is based on the character and distribution of subduction sutures and belts of arc-magmatic rocks, and on the lack of evidence for strike–slip faulting.

The outer part of the great arc of the Carpathian Mountains is coextensive with a belt of Tertiary thrust sheets, formed, in order concentrically inward away from the surrounding platforms, from synthrust Neogene foreland-basin strata; inner-shelf strata, Jurassic to middle Tertiary; outer-shelf strata, mostly Upper Cretaceous and Tertiary; and mostly deep-water Jurassic to middle Tertiary strata (see, for example, Unrug 1984). The inner part of the tract of deep-water materials includes much broken formation – extremely disrupted sedimentary rock (see, for example, Mastella 1988 – but otherwise the thrust belt consists of coherently deformed strata. Thrusting ceased at progressively younger time eastward, from very early Miocene in eastern Austria, progressively through the Miocene eastward across Slovakia, Poland, and Ukraine (Oszczypko & Slaczka 1989; Royden *et al.* 1983), to Pliocene at the east front of the arc in Romania.

Thrusting was radially outward around the entire arc: northwestward in western Slovakia, northward across the rest of Slovakia and Poland, northeastward in the Ukraine, eastward in central Romania, southward in southwest Romania. Deep-water materials were pushed up onto the outer continental shelf and shelf materials in turn were pushed cratonward. The thrust belt is largely a subsurface feature along the South Carpathians and is there buried by upper Neogene strata; apparently in that sector the overriding did not proceed far onto the pre-existing continental shelf.

In turn on the inner side of the belt of highly deformed deep-water strata is a concentric belt 1–20 km wide of polymict melange – chaotically disrupted and jumbled Triassic to middle Tertiary rocks, mostly sedimentary – that extends around the north limb of the arc from western Slovakia to northeast Romania (Birkenmajer 1985, 1986). The Upper Cretaceous and Palaeogene component of this melange is mostly deep-water clastic sediment, whereas older sedimentary rocks include both abyssal pelagic radiolarites and carbonate rocks and shallow-water carbonates; correlative rocks now juxtaposed occur in widely contrasted facies with quite different faunas. Crystalline rocks occurring as fragments and slices in the melange include glaucophane schist and ophiolite. Polymict melange may be lacking around the east end of the arc, although widespread broken formation, of deep-water Mesozoic through Oligocene clastic strata, is present in the same arcuate position. The equivalent belt is hidden by upper Neogene sediments along the east part of the south limb of the Carpathian arc, but along the west part polymict melange, including serpentinite-matrix melange, island-arc volcanic rocks, and continental basement rocks, reappear in the same structural position in a belt 25 km wide (Savu *et al.* 1986, 1987).

The melange of this great arc is classic subduction-complex material, and its components represent so varied a sampling of oceanic materials that it may record offscraping from thousands, not merely hundreds, of linear kilometres of subducted oceanic lithosphere. A collision, following subduction beneath an eastward-migrating arc of intervening oceanic lithosphere, with pre-existing continental shelves is indicated. The melange belt represents the unsubducted early formed part of the accretionary wedge of the advancing arc; the broken formation and deepwater sediments were accreted to the enlarging accretionary wedge as it neared the continent; the outer- and inner-shelf and foreland-basin parts of the thrust belt record the ramping of the entire wedge onto the continental shelf and the incorporation of shelf materials into the wedge. The collision was completed early in the Miocene in eastern Austria but terminated progressively later in the Miocene from Austria eastward through Slovakia, Poland, and the Ukraine, and not until the Pliocene at the east front of the arc in Romania. Benioff zone seismicity, hence slab sinking, and minor shortening still continue in Romania. I see this arc collision as due primarily to the eastward migration of a complex island arc into a remnant ocean, mostly of Jurassic lithosphere, left between continental masses incompletely sutured during late Mesozoic time. The advancing arc rode up on the surrounding continental crust progressively from west to east, like the breaking of a wave advancing into a bay, while the lengthening front of the arc continued to migrate eastward over the remaining oceanic lithosphere, with little if any strike–slip along the sides.

Behind the accretionary wedge, the arc was built partly on small continental-crustal masses, and partly was oceanic. A volcanic arc of basalt, andesite, and dacite, with subordinate rhyodacite and other rock types, trends irregularly and discontinuously along the inner part of the Carpathian arc. The volcanic rocks, like the great arc of accretionary-wedge materials, become younger eastward (Balla 1981*a*; Poka 1988). The volcanic rocks are of early and middle Miocene age in Slovakia, middle to late Miocene or Pliocene in the Ukraine, and late Miocene and Pliocene in the east part of the arc in Romania. No volcanic-arc rocks are exposed in the east part of the south limb, but in the Apuseni Mountains, north of the west part, they are again present and are of middle and late Miocene age. The ages of volcanic rocks indicate that the arc lengthened with time as it migrated and that the east part did not yet exist when the west part was colliding with the basin margins. This behaviour is analogous to that of the Banda Arc of eastern Indonesia during Neogene time, and probably to that of the Scotia and Caribbean arcs (Hamilton 1979, 1988). Similar volcanic-arc rocks form an extensive belt, mostly subsurface, that trends west-southwestward across Hungary from the southeast corner of Slovakia; whether these are paired to the main circum-Carpathian suture, to another suture, or to both is unclear.

The analysts favouring strike–slip emplacement of a continental plate into the pre-Carpathian embayment postulate left slip along the north limb and right slip along the south limb. The radially outward thrusting around the arc, the concentric distribution and character of subduction melange, and the age and distribution of volcanic-arc rocks are among the features inexplicable in these terms.

Unlike the outer part of the Carpathian arc, the inner part is irregular and poorly defined but can be designated as a belt, 50–100 km wide, of discontinuous mountains and uplands in which structural trends tend to be concentric to the accretionary wedge. This inner belt includes most of the volcanic-arc rocks noted above, and also Palaeogene and Cretaceous magmatic-arc rocks; a nearly continuous belt of highly deformed Mesozoic and Palaeogene deep-water sediments; and a discontinuous inner tract of crustal masses of widely varied crystalline rocks (mostly late Palaeozoic but including complexes as young as Palaeogene and at least as old as early Palaeozoic) and stratigraphically overlying and tectonically interspersed upper Palaeozoic, Mesozoic, and Cenozoic sedimentary rocks. The inner Carpathian tracts trend into the better known Austrian Alps and presumably like them contain complex sutures and collision complexes. Polymict melange and blueschist are known in southeast Slovakia and northeast Hungary (Balla 1983; Faryad 1988; Reti 1988; Szadeczky-Kardoss 1973), and polymict melange is widespread in parts of central Romania (Bombita & Savu 1986; Nastaseanu 1980).

The semicircular region, 400 km in diameter, of interspersed highlands and late Neogene basins inside the Carpathian arc is not a moderately disrupted continental plate but rather is a poorly understood aggregate of accreted terranes that records Mesozoic and Cenozoic rifting, drifting, and accretion. The highlands expose widely varying Mesozoic and Palaeozoic, and possibly Precambrian, metamorphic and magmatic complexes; diverse sections of non-metamorphosed upper Palaeozoic, Mesozoic, and Palaeogene deep-water, shallow-water, and non-marine strata; and Palaeogene and Miocene volcanic rocks, mostly of arc character (Balla 1981*a*; Berczi-Makk 1986; Foldvary 1988; Kazmer 1986). Similar rocks, and also melange and widespread Cretaceous and Tertiary calc-alkalic arc-volcanic rocks, are known in the many wells that penetrate upper Neogene strata (Fulop & Dank 1987). The Palaeozoic and Mesozoic crystalline complexes are of types produced in convergent-plate systems but their present chaotic distribution precludes palinspastic reconstructions with available data. Much of the exposed upper Palaeozoic and upper Palaeogene sections consists of terrigenous clastic sediments, whereas the Mesozoic and lower Palaeogene are dominated by limestone and dolomite (Berczi-Makk 1986; Kazmer & Kovacs 1985), much of it in thin pelagic sections deposited on isolated submarine platforms. Facies and sections differ greatly between neighbouring crustal blocks, and even more greatly between groups of blocks, which thus likely were widely separated before aggregation. Jurassic invertebrate fossils in limestones on the crustal fragments of the northern part of the inter-arc region are of southern Mediterranean types, whereas those in the southern part are much more like those of Europe to the north: the palaeogeographic positions of the fragments not only have been reversed by complex subsequent plate motions, but the tracts likely were far apart in Mesozoic time (Burtman 1984).

Ophiolite and polymict melange, including widely varied Late Mesozoic abyssal materials, exposed in some uplands – northeast Hungary and central Romania, as noted previously; south Apuseni Mountains, Romania (Cioflica & Nicolae 1981; Savu 1984); probably southwest Hungary (Balla 1981*b*) – require subduction between continental crustal blocks now juxtaposed. A major belt of Tertiary melange crosses Hungary and northwest Romania. How much of the total subduction recorded is Mesozoic and how much Tertiary remains to be established.

The widespread exposed and subsurface Cretaceous and Tertiary volcanic rocks of arc types presumably were byproducts of diverse subduction systems operating between crustal blocks and island arcs now aggregated in the broad region inside the Carpathian arc (Balla 1981*a*, but cf. Balla 1986; Szadeczky-Kardoss 1973), although magmatic rocks cannot yet be confidently paired to correlative sutures with either surface or subsurface data. A mostly subsurface Miocene volcanic arc, 50 km wide, of andesites and allied rocks trends east-northeastward across all of Hungary, through the centre of the intra-Carpathian region (Balla 1981*a*; Szadeczky-Kardoss 1973). The intra-Carpathian region must record a long and complex history of rifting and convergence, including subduction of numerous oceanic plates of various sizes.

The Miocene volcanic arc noted in the preceding paragraph lies along the north side of, and may be wholly or partly paired to, a major Tertiary suture, crossing Hungary and Romania within the intra-Carpathian region, which separates the reversed-position northern and southern assemblages that were noted above. The suture was recognized as such by Szadeczky-Kardoss (1973) and forms a belt, about 50 km wide and trending west-southwestward in the subsurface of eastern Hungary, of broken formation and melange, the Senonian and Palaeogene flysch of Fulop & Dank (1987). The belt consists of highly tectonized middle Cretaceous basalt and abyssal pelagic sediments, and Upper Cretaceous through upper Oligocene marls and turbidites (Baldi-Beke *et al.* 1981; Z. Balla & T. Szederkengi, personal communication 1988; Szadeczky-Kardoss 1973). L. Lakatos translated for me descriptions of cores from four oil-exploration wells that penetrated 150–500 m into the complex. Rocks bearing Cretaceous and Palaeogene pelagic foraminifera are jumbled together with clasts containing shallow-water fossils. The descriptions are full of terms that translate as 'very dislocated', 'bright sliding surfaces', 'strong brecciation', 'shiny shear surfaces', and so on. Scaly-clay broken formation is thus widespread and polymict melange probably is extensive. I studied seismic-reflection profiles across the belt, and these show the melange as acoustic basement, devoid of coherent internal reflections, overlain by undeformed upper Miocene and younger strata. I infer formation in an accretionary wedge recording the subduction of at least hundreds of kilometres of oceanic lithosphere; and I regard as disproved the suggestion by Royden & Baldi (1988) that the complex is the Palaeogene fill of a narrow transtensional basin formed in a hypothetical strike–slip system. If the volcanic arc noted did indeed form paired to the suture, then the subduction recorded was northward beneath the northern tract. Linear anomalies shown on the magnetic map of Hungary within the obvious melange belt and west-southwest on trend from it are due primarily to Cretaceous basalt, according to sparse basement-well data as summarized schematically by Fulop & Dank 1987; I infer that the suture continues in the subsurface across southwest Hungary.

Along strike in the other direction, the suture zone crops out in north-central Romania in the 'Maramures Transcarpathian zone' (cf. Dicea *et al.* 1980; Sandulescu 1980), a belt of polymict melange, broken formation, and scaly clay that includes abundant fragments of ophiolite and abyssal sedimentary rocks, and disrupted deep-water clastic strata at least as young as Oligocene. The suture complex swings northeastward into northeast Romania and there merges with the polymict melange belt of the main Carpathian arc. I deduce that the middle Tertiary northeast-trending suture complex was in part recycled into the late Tertiary suture that there trended southeast.

Many small basins, irregular, diversely oriented, and filled by upper Neogene strata, lie in the intra-Carpathian region, primarily in Hungary (Fulop & Dank 1987) but also in each of the adjacent countries. The upper strata (the late Miocene and younger Pannonian facies) represent largely the passive filling, in general by deltas prograding from the northwest followed by lacustrine and terrestrial sedimentation, of pre-existing depressions (Mattick *et al.* 1985). The nature of most of these depressions is not established. I have looked at many published and unpublished seismic-reflection profiles across the basins. Profiles across many basins show no clear structure other than compaction in their fill. Other profiles show middle and late Miocene syndepositional shortening, for strata are continuous across asymmetric folds that define the sub-Pannonian basins, and depocentres migrate basinward going upward in the sections. Two basins – Bekes in southeast Hungary and adjacent Romania, and the southeasternmost Slovakian basin – likely mark unclosed oceanic–lithosphere 'holes', for they have positive Bouguer gravity anomalies whose amplitudes increase with increasing thickness of fill. The visualization of the Carpathian ocean gap as having been filled by a sliced continental plate in general assumes the basins to record oblique extension between linked strike–slip faults (see, for example, Royden 1988; Royden *et al.* 1983), but the assumed character of basins and faults has not been established by either outcrop or subsurface data.

The middle Tertiary suture and Miocene volcanic arc across Hungary indicate that the aggregation of the intra-Carpathian region was completed during, not before, the migration of the Carpathian arc over subducting oceanic lithosphere. It follows that the intra-Carpathian gap was broader in Palaeogene time than it is now, and that the gap was shortened from north to south by the intra-Carpathian subduction. Tertiary melange in central Romania, and middle Tertiary arc-volcanic rocks scattered about the region, presumably are also products of syn-Carpathian suturing. I see the intra-Carpathian region as produced by the squashing together of a number of small continental and island-arc fragments during Tertiary time, a view opposite to the common concept that its Tertiary history records primarily the moderate disruption of a previously coherent mass.

How many small continental and island-arc plates (terranes) are there, when and how were they aggregated, and where were they before and during aggregation? Obviously, my brief analysis raises many more questions than it answers. Evaluation is needed of the tectonic, stratigraphic, palaeoenvironmental, palaeobiogeographic, and magmatic history of each of the many possible thick-crustal masses, exposed and subsurface, in the inner-arc and intra-Carpathian regions. The region thus needs terrane analysis, which must however be integrated with actualistic plate tectonics.

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Discussion

P. D. Clift (*Grant Institute of Geology*, *University of Edinburgh*, *U.K.*). Tectonic reconstructions of active continental margins involving large-scale, along strike motion of accreted continental and oceanic terranes may have only a limited application to narrow ocean basins, such as those whose closure formed the European Alpine system. The absence of island-arc terranes from suture zones any further west than the Aegean Sea, together with palaeomagnetic data from the African and Eurasian plates constrains the western Tethys to being a relatively small embayment of a larger easterly ocean, and experiencing only limited along strike motion due to different times of opening of the central and north Atlantic Ocean. Continental terrane motion was thus broadly a north to south migration. Despite the small size of the oceans, the rates of continental rifting and oceanic subduction, along the margin of Neotethys, were, however, comparable with modern circum-Pacific examples, although in the Tethyan case punctuated by long period of relative tectonic quiescence.

W. B. HAMILTON. Although Dr Clift is of course correct that western Tethys was a narrow ocean, I disagree with his derivative assumptions. He suggests that motions of intra-Tethyan plates were primarily meridional, but Italy has moved eastward over a subducting Adriatic plate (Dewey *et al.* 1989), Corsica and Sardinia also have migrated primarily eastward, and the advancing arc that collided with the Spanish and African margins of what is now the Alboran Sea must have had a large westward component of motion. My analysis of the Carpathian arc as eastward-migrating is given in the preceding text.

Nor are island arcs lacking west of the Aegean Sea; magmatic-arc rocks, variously oceanic, continental, and hybrid, are voluminous in the Dinarides, Carpathians, and Italy, and present in lesser quantities in other parts of the western regions. Some western Tethyan complexes may well record major subduction.

A. H. F. ROBERTSON (*Grant Institute of Geology, University of Edinburgh, U.K.*). Palaeomagnetic evidence appears to suggest that much of southern Greece and Turkey (at least) originated near the northern margin of Gondwanaland rather than far to the east in the ancestral Pacific ocean. Other units, especially those located along the northern margins of the Tethys (e.g. Pontides) may be much more exotic, however. The implication that plate displacement rates were unusually slow is perhaps misleading. At least along the North Gondwana margin relatively rapid events (e.g. Triassic spreading in several small ocean basins) were separated by long periods of relative quiescence (e.g. with development of passive margins). Rapid displacements were often episodic, for example, as a consequence of the motion of larger plates (e.g. Late Jurassic opening of the North Atlantic, Cretaceous opening of the South Atlantic).

W. B. HAMILTON. Dr Robertson, like Dr Clift, infers that intra-Tethyan motions were episodic, periods of rapid plate migrations having been separated by long periods of stability. Although long-continuing passivity of specific continental margins or small plates is indeed obvious, other western Tethyan plates and margins were undergoing deformation and magmatism during at least most of Mesozoic and Cenozoic time. Such contrasts – passive here, subducting there – necessarily typify all regions of moving plates, and are not indications of episodicity.

Palaeomagnetic evidence, as referred to by Dr Robertson, can not constrain palaeolongitude, and so can provide at best only part of the data needed to cope with the problems of an ocean that was elongate east–west. Palaeontologic evaluation is needed to define biogeographic provinciality and to explore the possibility of large offsets of displaced materials within the vast Tethyan complexes.