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COMPARISON OF SUBDUCTION ZONES VERSUS THE GLOBAL TECTONIC PATTERN: A POSSIBLE EXPLANATION FOR THE ALPS-CARPATHIAN SYSTEM*

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Apparently, plates are not moving randomly over the Earth's surface but rather following a common flow. Moreover the sum of plate motions detected in the hot-spot reference frame indicates that plates are moving 'westward' relative to the mantle. A reference point within the mantle should then move 'eastward' passing beneath different sections of the lithosphere, enabling a mantle source to be located at different times under continental or oceanic lithosphere. This can also explain the major differences between thrust belts related to subductions following or opposing the relative 'eastward or northeastward' mantle counter flow. These statements could provide a tool for the Alps-Carpathian puzzle. The Alps are a thrust belt mainly related to an E-dipping subduction following the 'eastward' mantle flow. They have high elevation, shallow foredeep, deep crustal rocks involved and no back-arc basin. In contrast, the Carpathians are related to a subduction opposing the 'eastward or northeastward' mantle flow, they have low elevation, deep foredeep, shallow rocks involved and the Pannonian back-arc basin. The Central-Eastern Alps are characterized by dextral transpression, the Western Carpathians by sinistral transpression. The Vienna Basin is located in the area of transfer between the two systems controlled by different subduction polarity.

Keywords: tectonics, subduction zones, thrust belts, Alps-Carpathian system

1. Introduction

The relative motion vectors between lithosphere and underlying mantle appear to follow global flow lines (*Fig. 1*) which can be constructed by linking axes of extension and compression over the Earth's surface [DOGLIONI 1990]. The flow lines of the last 40 Ma are generally WNW-ESE (E-W), with an about 15 000 km wavelength undulation showing gradual and progressive

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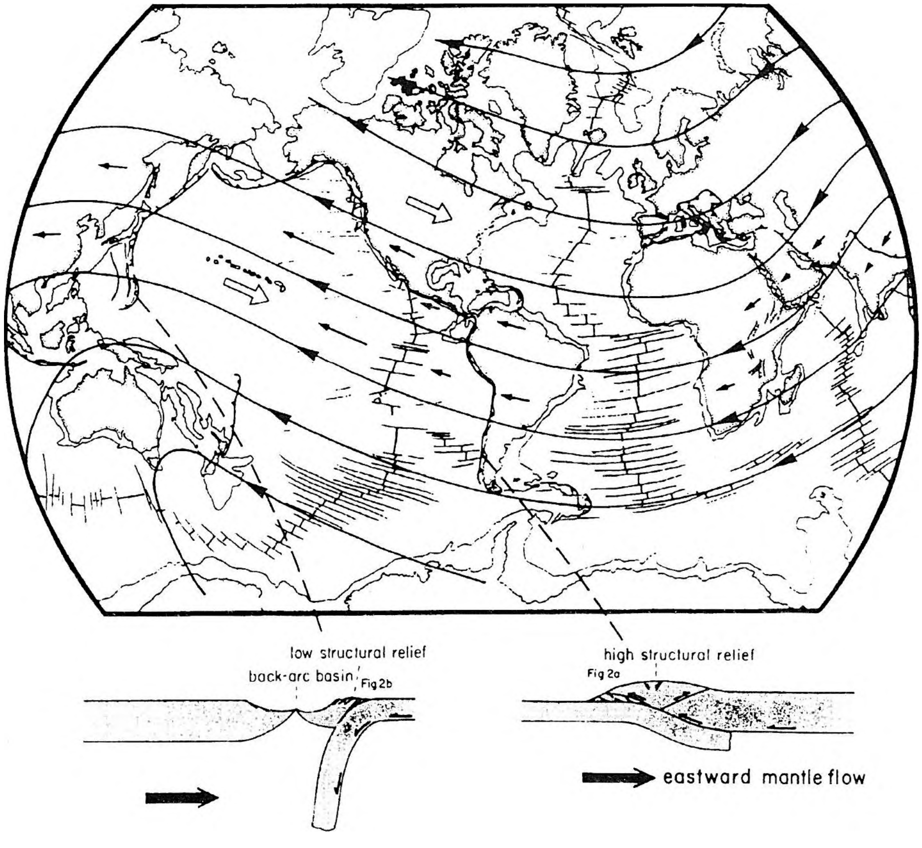

Fig. 1. This map shows the inferred flow lines along which plates move relative to the underlying mantle. These flow lines also indicate the westward polarity of plate motions (small black arrows) relative to the eastward mantle flow (big white arrows). Note below that this global tectonic polarity is responsible for the different dip of the subduction zones. The locations of Fig. 2a and Fig. 2b are shown. [Modified after DOGLIONI 1990]

1. ábra. A térkép a köpenyhez képest mozgó lemezek feltételezett áramlási vonalait mutatja. Ezek az áramlási vonalak a lemezmozgások nyugati polaritását is jelzik (kis fekete nyilak) a keleti irányú köpenyáramláshoz képest (nagy fehér nyilak). Figyeljük meg a térkép alatti két rajzon, hogy ez a globális tektonikai polaritás okozza a szubdukciós zónák eltérő lehajlását. A 2a és 2b ábrák helyeit feltüntettük. [DOGLIONI 1990 nyomán]

Рис. 1. На карте показано предпологаемое направление движения плит относительно мантии. Линии течения показывают также и западное движение плит (мелкие черные стрелки) относительно к восточному мантийному течению (большие белые стрелки). По рисункам, расположенным под картой, можно выявить, что эта противоположная глобальная тектоническая полярность вызывает противоположное направление субдукции. Отмечены участки, показанные на Рис. 2a и 2b. [По DOGLIONI 1990] variation in orientation. Plate tectonics can be analysed taking into account the net westward s.l. drift of the lithosphere relative to the mantle [LE PICHON 1968, BOSTROM 1971, NELSON, TEMPLE 1972], which is not an artifact of a particular hot-spot reference frame but a real physical observation which can be produced in a toroidal field by the lateral heterogeneities both in the mantle and in the lithosphere [RICARD et al. 1991]. On this basis plate tectonics may be considered as a consequence of variable decoupling at the lithosphere base as a function of the mantle anisotropies [DZIEWONSKI 1984, RICARD, VIGNY 1989, DOGLIONI 1990]. Simply stated, when there is compression or transpression between two plates, it is the eastern plate which moves faster westwards relative to the underlying sublithospheric mantle. If there is extension or transtension, it is the western plate that moves faster westwards or, more precisely, along the undulate global flow of the lithosphere. Lithospheric subduction [DEWEY 1981, UYEDA 1982, VON HUENE, LALLEMAND 1990], especially if it dips westward, produces an obstacle to the eastward flow of the mantle [NELSON, TEMPLE 1972, UYEDA, KANAMORI 1979]. Plates move following a well defined global tectonic pattern (Fig. 1) showing a major undulation of motion between eastern Africa and western Pacific [MINSTER, JORDAN 1978, GORDON, JURDY 1986, DOGLIONI 1990]. The same plate motion directions have been pointed out by geodetic satellite analysis [SMITH et al. 1990]. This paper tries to compare the general features of thrust belts with the subduction zones following (E- or NE-dipping) or contrasting (W- or SW-dipping) the mantle flow (Fig. 1). This subdivision seems to be more important with respect to the thickness and type of lithosphere involved in the collisional processes.

An E-dipping subduction can start only if there is an original thinner lithosphere to the west relative to a thicker lithosphere to the east. In contrast, we need to activate a W-dipping subduction in the presence of a thinner lithosphere to the east relative to a thicker one to the west. This is independent of the nature of the subducted lithosphere (both oceanic and continental). However the thinner and more oceanic lithosphere subducts more easily. Lateral thickness variations are a first order factor in controlling the amount and style of subduction. Moreover, longitudinal lithospheric variations in thickness and composition are able to produce strong asymmetry along the subduction zones, e.g. the Apennines which are characterized by a thin crust in the Ionian Sea and a relatively thicker crust in the Adriatic Sea to the north along the W-dipping subducting slab.

2. Subductions versus thrust belts

E- (or NE-) dipping subductions follow the mantle flow (Fig. 1). They are associated with thrust belts with huge exposures of basement rocks (also lower crust), high structural and morphologic reliefs in contrast to limited and usually shallow foredeeps (e.g. American Cordilleras, Western Alps, Dinarides, Zagros, Himalayas, *Fig. 2a*). The area of active compression may be very wide (hundreds of km), with extensional isostatic collapses in the internal core [PLATT 1986, DEWEY 1988]. Only in this kind of thrust belt have coesite-pyrope-bearing assemblages and eclogites been found [CHOPIN 1984, WANG et al. 1989], confirming that thrust sheets have detachment planes connected with depths ranging between 20 and 30 kbars (almost the lithosphere base). Collision should continue until the vertical lithostatic stress exceeds the horizontal shear values.

W- (or SW-) dipping subductions contrast with the mantle flow. They are instead associated with thrust belts involving high layers of the crust, back-arc basins and very consistent foredeeps generated by the roll-back of the subduction hinge (e.g. West Pacific accretionary wedges, Barbados, Apennines, Carpathians, *Fig. 2b*). W-dipping subductions are characterized by an eastward migrating tectonic wave (back-arc extension to the west and compression to the east). The extension continuously propagates and cross-cuts into the previously formed thrust belt. The area of active compression in this kind of thrust belt is very narrow (a few tens of km). Deep rocks may be involved in this type of accretionary wedge only if they were in a high structural and morphologic position before the onset of the W-dipping subduction (e.g. the granulite rocks of Calabria which emplaced during an earlier Eoalpine E-dipping subduction). The accretionary wedge is mainly formed by stacking of upper layers of the lower plate.

Note that in the E-dipping subductions the basal and intralithospheric decollements of the eastern actively thrusting plate are transmitted at the surface and provide a mechanism for bringing deep crustal levels to the surface (Fig. 1), whereas in the W-dipping subductions the base plate detachment is never connected to the surface, but it is rather folded and subducted itself. In fact the W-dipping case produces more superficial detachments in the accretionary wedge spatially followed by an eastward migrating extensional wave.

The two types of thrust belts should be considered as two end members. Oblique and lateral subductions (e.g. the Gibraltar arc, Betics and Maghrebides, etc.) have to be further distinguished in between. In fact, thrust belts parallel or slightly oblique to the mantle flow (Chaman transform zone, Central Alps, Pyrenees, Maghrebides etc.) are in general connected to body forces and/or second order rotations of blocks. Further distinctions have to be made on the basis of the relative thickness and viscosity contrasts between colliding plates, e.g. oceanic and continental (Andes) or continental collision (Himalayas): both are related to subductions following the mantle flow, but they are associated with different pre-existing lateral heterogeneities in the lithosphere which control the amount and kind of subduction.

A third type of subduction and related thrust belt is that produced by localized rotation of microplates, e.g. the counterclockwise rotation of Spain which produced the Pyrenees. This kind of subduction does not generally follow the mantle flow and is associated with very low or absent volcanism.

The origin of foreland basins in the two different thrust belts could consequently be controlled by different geodynamic factors: In the E-dipping case with the load of the thrust sheets [QUINLAN, BEAUMONT 1984], whereas in the W-dipping subduction, where the topographic load is insufficient to generate deep foredeeps basins [ROYDEN, KARNER 1984], the subsidence is allowed by the eastward retreating of the subduction hinge, due to the eastward push of the mantle. Dextral transpressive subductions characterize E-W oriented chains like the Central-Eastern Alps, the Betics and Maghrebides chains. Then a third type of foredeep is that produced at the transpressive subductions (e.g. the Venetian foredeep in front of the Southern Alps), or in front of thrust belts produced by rotation of microplates (e.g. the Pyrenees).

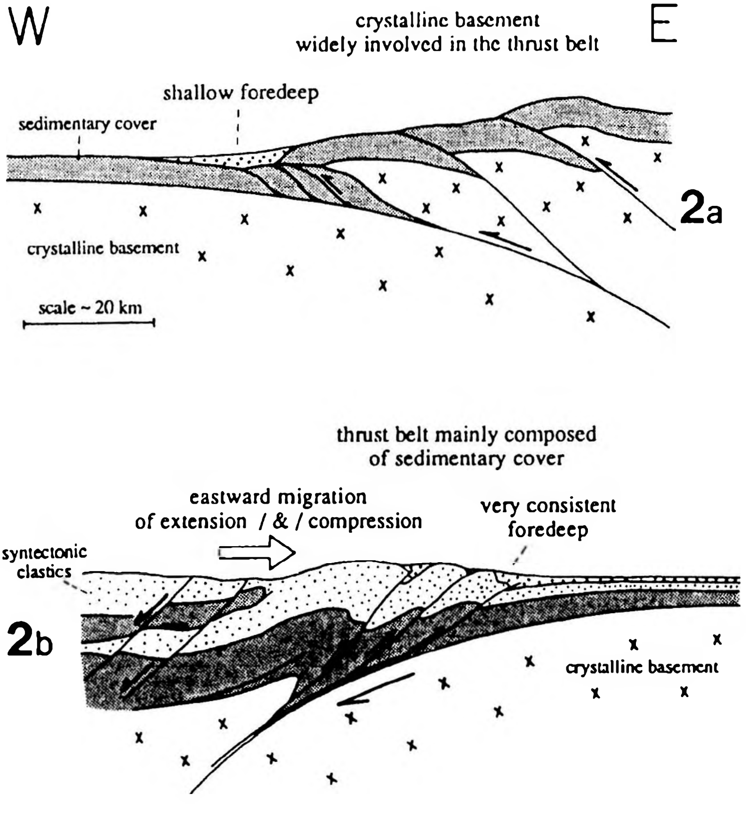

Fig. 2. Main features and structural differences between thrust belts associated with E-dipping (2a) and W-dipping (2b) subductions

2. ábra. A kelet felé (2a) és a nyugat felé (2b) hajló szubdukciókhoz kapcsolódó gyűrődéses övek fő vonásai és a közöttük lévő szerkezeti különbségek

Рис. 2. Характеристика и главные структурные различия складчатых поясов, связанных с восточной (2a) и западной (2b) субдукцией

3. Discussion

E-dipping subductions almost everywhere activate a backthrusting accretionary wedge, like all the southern and northern American Cordilleras. Consequently these E-vergent thrust belts with metamorphic core complex (e.g. Rocky Mountains) are related to E-dipping subductions and have to be distinguished from E-vergent thrust belts associated with W-dipping subductions characterized by the shallow rocks involved [e.g. the Apennines, BALLY et al. 1986]. We can also note that in W-dipping subductions the tangent to a pre-deformation marker descends into the trench, while in E-dipping subductions the same marker would rise towards the hinterland (Fig. 2). Moreover from the lithology of old thrust belts we could reconstruct whether they were formed during E- or W-dipping subductions: the deep rocks of the Caledonides should then have been formed with a subduction following the mantle flow. From the present orogenic belts and from their associated subduction we can predict the pre-existing shape and geographical position of the lithospheric stretching: this is a new tool in the reconstruction of Tethyan basins. Another consequence of the model is that magma sources positioned in the mantle might continuously move along the flow lines, i. e. bringing the continental mantle beneath the oceanic crust (*Fig. 3*).

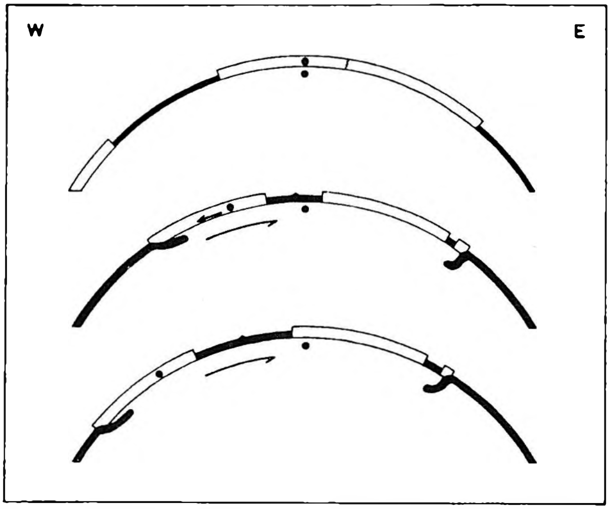

Fig. 3. Schematic representation of the westward rotation of plates relative to the underlying mantle. Note that the reference point in the mantle is continuously moving below a different lithosphere

3. ábra. A lemezek köpenyhez viszonyított nyugati irányú forgásának vázlata. Figyeljük meg, hogy a köpenybeli referenciapont mindig más litoszféra alá mozdul el

Рис. 3. Схема западной ротации плит относительно к мантии. Наблюдается, что мантийная точка относительности движется под разными литосферными блоками

4. Regional application of the model

We now try to investigate the Alps-Carpathian system in terms of the global tectonic pattern. For a recent review of the two main features, see ROYDEN, HORVÁTH [1988] and COWARD et al. [1989] and references therein. In the Carpathian-Pannonian basin, subsidence starts at the Badenian (16.5 Ma), and thrusting in latest Oligocene-early Miocene. ROYDEN et al. [1982] described an eastward migration of the volcanic activity, a current vertical slab, estimated by fault plane solutions, and a downbending of the subducted plate. The estimated extension (75 km west Carpathians —100 km east) is comparable to the synchronous crustal shortening and the foredeep is about 8 km deep [ROYDEN, KARNER 1984].

Farther west, the NE-dipping Dinaric subduction started at least in the Late Cretaceous times and partly stopped in the Miocene [BURCHFIEL 1980]. The dipping of the slab is gentle and the foredeep depth ranges between 3-4 km. Due to the lack of data, no estimation of the shortening has been published. The Variscan basement widely crops out in the internal zone.

On the other side of the Adriatic Sea the Northern Apennines, characterized by a W-dipping subduction, display a completely different geometry. The foredeep is quite deep like in the Carpathians, up to 8 km at the Messinian reflector, and the strong flexure of the subducting plate cannot be explained by the topographic load of the chain [ROYDEN, KARNER 1984]. Even if the basement has to be involved in depth by the thrusting, it never crops out (apart from limited internal zones, e.g. Apuane Alps, Tuscany), and the main decollement level is the top of the Trias and the thrust sheets are formed by the sedimentary cover.

Recent deep seismic data of the Alps allowed new structural interpretations of the chain. In the Alpine section, W-vergent thrusting cutting throughout the crust into the mantle supports the 'obduction' of the Adriatic plate on to the European foreland. The Alps are the product of the Late Cretaceous to the present closure of a lithosphere thinned during Late Permian-early Middle Mesozoic. In spite of several paleogeographic problems, we shall try to analyse alpine tectonics in terms of relative activity of the decollement at the base of the lithosphere. During the initial phases of extension the western European continent should have had a plane of detachment more active with respect to the eastern Adriatic plate in order to produce the Tethyan rifting. The Cretaceous inversion [DAL PIAZ et al. 1972, POLINO et al. 1990] would correspond to the inversion of the relative velocity which should become greater at that moment beneath the Adriatic plate. Kinematic indicators in the Central Alps give a dominant E-W or NW-SE sense of relative motion from Late Cretaceous time [PLATT et al. 1989] suggesting that the motions of Adria and Africa were more or less independent from that time and characterized by different amounts of decoupling at their base. The plate margins evolved through time as a function of differences in plate velocity, e.g. the northern Adriatic plate margin was represented by the Austroalpine units during extensional phases and Eoalpine and probably Mesoalpine inversion, while it is now represented at the surface by the Insubric Lineament which is the present boundary of relative plate velocity contrast. In order to get dextral transpression along the Insubric fault zone we need a greater detachment at the Adriatic plate base with respect to the European one. Extension occurred within the Alpine edifice and around it at different stages of the orogenic evolution [e.g. the Oligocene phase, LAUBSCHER 1983]. This extension [DAL PIAZ 1976] has also been interpreted as due to isostatic re-equilibrations [PLATT 1986, DEWEY 1988]. Another possibility is that the load and the thickening of the lithospheric doubling in the E-dipping subductions would produce a disactivation (or decrease) of the detachment at the base of the eastern plate, generating a relatively greater westward drift of the western plate, which is responsible for extension. In other words, the collision should pass alternating phases of compression or extension as a function of the activity of the basal (or intra) lithospheric detachments. *Fig. 4* presents a schematic picture of the Neogene to recent Alps-Carpathian system pointing out that the main frame might be analysed in terms of different westward decoupling of the lithosphere relative to the mantle.

The Mediterranean region might be interpreted in terms of differences of the base lithosphere decoupling [DOGLIONI et al. 1991]. The detachment occurs at the base of an anisotropic and segmented lithosphere which overlies an eastward (northeastward) directed mantle flow. This is in agreement with the general eastward rejuvenation of extension and magmatism observed in the Central-Western Mediterranean. The region is located within the global undulation of the flow lines interpreted as generated by the instability of the rotation axis. In fact the main motion of the mantle relative to the lithosphere seems to be E-W directed in the western Mediterranean, gradually changing to ENE-WSW trends [MANTOVANI et al. 1987] in the eastern regions. Regional variations in the general trend may be interpreted as due to body forces like transpressions or transtensions (e.g. the Central-Eastern Alps, the Betics and Maghrebides, or the Southern Carpathians) or to second order tectonic fields produced by rotations of microplates (e.g. the Pyrenees) which could generate for instance N-S compressions. The Mediterranean tectonics is a good example of lateral variations in lithosphere thicknesses and compositions, which are fundamental factors in controlling the rate of subduction and the relative velocities among plates.

5. Concluding remarks

The model described in the previous sections is applicable to the Mediterranean where the eastward or northeastward relative migration of the underlying mantle with respect to an inhomogeneous disrupted lithosphere could explain the puzzling tectonic evolution of this area [DOGLIONI et al. 1991]. The geodynamics is complicated by N-S compressions resulting from second order rotations (e.g. Spain and Adriatic plates) and transpressions induced by body

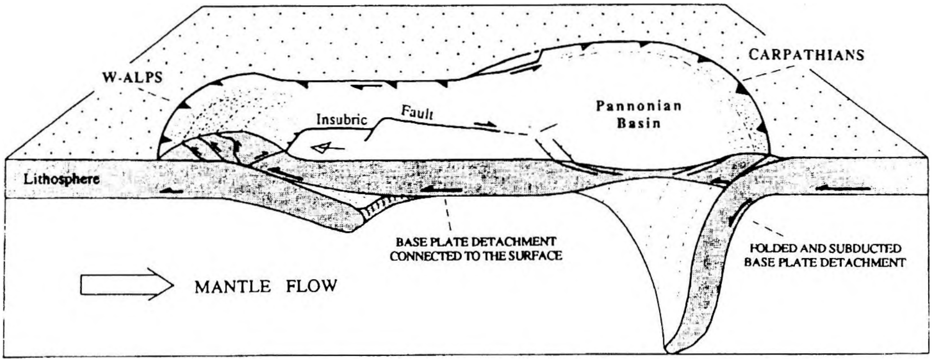

Fig. 4. Schematic picture of the Neogene to recent Alps-Carpathian system analysed in terms of different relative westward velocities of the lithosphere relative to an eastward-northeastward directed mantle flow. Note that the back-arc extension in the Pannonian Basin is a direct consequence of the eastward retreating of the W-dipping subduction hinge zone due to the eastward push generated by the mantle flow. Note that the Vienna Basin is the area of separation between the relative plate motions producing dextral transpression in the Central-Eastern Alps and sinistral transpression in the Western Carpathians. [After DOGLIONI et al. 1991]

4. ábra. A keleti-északkeleti irányú köpenyáramláshoz képest nyugat felé mozgó litoszféralemezek sebességkülönbségei alapján megrajzolt vázlat az Alpok-Kárpátok rendszer kialakulásáról a neogéntől napjainkig. Figyeljük meg, hogy az ív mögötti extenzió a Pannon medencében közvetlen következménye a nyugat felé hajló szubdukciós zóna keleti irányú hátrálásának, amelyet a köpenyáramlás keleti irányú tolóhatása eredményez. Látható, hogy a Bécsi medence a Közép-Kelet-Alpokban jobbos, a Nyugati-Kárpátokban pedig balos transzpressziót okozó relatív lemezmozgásokat elválasztó terület. [DOGLIONI et al. 1991 nyomán]

Рис. 4. Схема происхождения Альпийско-Карпатской системы с неогена до современности, построенная по разности скорости западного движения литосферных плит относительно мантийному течению. Обнаруживается, что задужная экстенсия в Паннонском бассейне является непосредственным следствием перемещения на восток зоны субдукции с западным склонением, что связано с восточным движением мантийного течения. Показано, что Венский бассейн является участком, разделяющим Центральные-Восточные Альпы, где относительное движение плит вызывает правую транспрессию, от Западных Карпат, где оно приводит к левой транспрессии. [По DOGLIONI et al. 1991]

forces. The present Mediterranean or Alpine-Carpathian shape (Fig. 4) is a direct function of the inherited Mesozoic lateral heterogeneities of the lithosphere, which are, in turn the key point for relative differences in velocity and subduction. LAUBSCHER [1988] and ROYDEN and BURCHFIEL [1989] pointed out the main differences between 'Alpine' thrust belts (push arc) and 'Apenninic or Carpathian' thrust belts (pull arc). These differences may be interpreted as a consequence of the different position and behaviour of the detachment planes in west or east dipping subductions.

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A SZUBDUKCIÓS ZÓNÁK ÉS A GLOBÁLIS TEKTONIKA ÖSSZEHASONLÍTÁSA: AZ ALPOK-KÁRPÁTOK RENDSZER KIALAKULÁSÁNAK EGY LEHETSÉGES MAGYARÁZATA

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A lemezek nyilvánvalóan nem rendezetlenül mozognak a Föld felszínén, hanem egy közös áramlási irányt követnek. Sőt a hot-spot vonatkoztatási rendszerben megfigyelt lemezmozgások összege azt mutatja, hogy a lemezek a köpenyhez képest „nyugat felé" mozognak. Így egy köpenybeli vonatkoztatási pontnak a litoszféra különböző részei alatt elhaladva „kelet felé" kell mozognia, így ugyanaz a köpenybeli forrás különböző időpontokban egyszer a kontinentális, máskor az óceáni litoszféra alatt található. A fenti elmélet megmagyarázhatja a „keleti vagy északkeleti" köpenyáramlással azonos, illetve ellentétes irányú szubdukciókhoz kapcsolódó gyűrődéses övek fő különbségeit. Ezen állítások segítségével közelebb juthatunk az Alpok-Kárpátok rendszer megértéséhez. Az Alpok egy olyan gyűrődéses öv, amely a „keleti" köpenyáramlással azonos irányú, kelet felé hajló szubdukcióhoz kötődik. Nagy tengerszint feletti magasság, sekély előtéri medence, a kéreg mélyebb részeiből származó kőzetek és az ív mögötti medence hiánya jellemzik. A Kárpátok ezzel ellentétben a „keleti-északkeleti" köpenyáramlással szemben végbement szubdukcióhoz kapcsolódik, így kisebb tengerszint feletti magasság, mély előtéri medence, kis mélységből származó kőzetek és a Pannon, ív mögötti medence jellemzik. A Közép-Kelet-Alpokban jobbos transzpresszió, míg a Nyugati-Kárpátokban balos transzpresszió figyelhető meg. A Bécsi medence e két különböző irányítottságú szubdukciós rendszer által kijelölt átmeneti területen helyezkedik el.

СОПОСТАВЛЕНИЕ ЗОН СУБДУКЦИИ И ГЛОБАЛЬНОЙ ТЕКТОНИКИ: ВОЗМОЖНОЕ ОБЪЯСНЕНИЕ ПРОИСХОЖДЕНИЯ АЛЬПИЙСКО-КАРПАТСКОЙ СИСТЕМЫ

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Движение плит на поверхности Земли явно не является беспорядочным, а соответствует некоторому общему направлению. Суммирование наблюдаемых движений коры показывает, что плиты движутся в западное направление относительно мантии. Следовательно, если точку относительности разместить в мантию, то она должна двигаться на восток под разными частями литосферы, и поэтому тот же источник в разное время может находиться как и под океанической, так и под континентальной литосферой. Такая гипотеза может объяснить различия между складчатыми поясами, связанными с субдукцией по направлению согласной и противоположной восточному или северо-восточному мантийному течению. Применение такой гипотезии способствует интерпретации Альпийско-Карпатской системы. Альпийский складчатый пояс связан с субдукцией в восточном направлении, т.е. в направлении мантийных течений.

Он характеризуется значительной высотой над уровнем моря, неглубокой предгорной впадиной, наличием пород, образовавшихся в глубоких зонах коры и отсутствием задужного бассейна. Наоборот, Карпаты связаны с субдукцией в противоположном мантийным течениям направлении и характеризуются меньшей высотой, глубокой предгорной впадиной, породами, образовавшимися в небольшой глубине, и наличием Паннонского — задужного — бассейна. В Центральных-Восточных Альпах наблюдается правая, а в Западных Карпатах—левая транспрессия. Венский бассейн находится на промежуточной территории между двумя системами.