Arc-continent collisions: general regularities

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Abstract**—**The arc-continent collision is a process which is described in many Phanerozoic foldbelts; there are examples of active collisional orogens of such type among them. It is shown that the origin and development of arc-continent collisional orogens is subordinate to some regularities and laws. They happen only as a collision of an arc with a passive continental margin, and only in case when a subduction zone dips out of a colliding continent. The collisions are accompanied by a dramatic change of a terrigenous provenance and are characterized by exhumation of HP-LT metamorphic complexes. To date these events means to date the collision. The orogenic structures accompanying the collision follow general regularities of a critical wedge theory and model. One of the consequences of this theory is a regular "nappe stratigraphy" where the age of a nappe depends on its position in a nappe stack (the higher, the older). As for the lateral rows of structures, seismic images of foreland structures reveal in some cases a transition from "thin skinned" tectonics to "thick skinned" and then to a suture zone with predominant squeezing and crushing. The collisional structures "in plan" reveal plastic features and ability of oroclinal deformations, in contrast with "ideal" rigid lithospheric plates. The arc-continent collisions often demonstrate diachroneity, when one flank of an arc collides earlier then another, suggesting that they are rather random, depend on local conditions and not subjected to a strict global rhythm.

Keywords**—**Continents, collision, island arcs, tectonic phases and cycles.

I. Introduction

ANY collision is a consequence and result of a subduction, when an easily subducted oceanic lithosphere between two sialic blocks completely disappears in mantle, and these light blocks come into a contact, being incapable of a further subduction.

Looking at the modern Pacific ring of subduction zones, one may say that arc-continent collisions are not typical or improbable, but it is not so. Even in this ring there is an excellent example of a present-day collision of Luson arc and a passive margin of the Eurasian continent, leading to a formation of Taiwan island and orogen. More ancient (Early Paleocene) example is a collision between the Bigger Antilles arc and Florida promontory of the North American continent. A bright example is a modern collision between the Sunda arc and Australian continent (Fig.1). In the Mediterranean sector of the Alpine foldbelt such collisions were typical, and we can see now the final stages of a collision between the Tyrrhenian arc and Gondwana blocks. Still more examples can be taken from the Paleozoic history, which we are going to look at in more detail.

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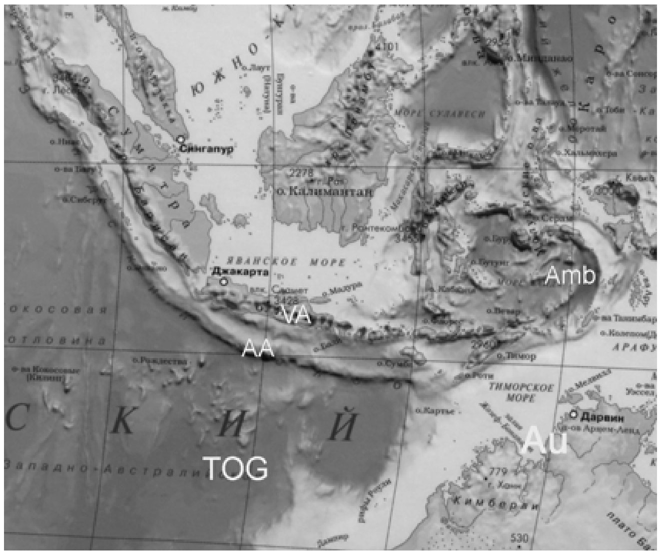

Fig.1. Sunda–Ambon arc, a partial collision with the Australian continent. TOG – triangular oceanic gap, Amb – Ambon arc, AA and VA – avolcanic accretionary and volcanic Sunda arcs correspondingly. Au – Australian continent

II. The aim of the study

The aim of our study is to reveal main regularities of process of arc–continent collision and its place in making the Earth's crust. The most important issues are:

- the conditions leading to the process;
- ways of its exact dating, according to a time of specific changes in a sedimentation and onset of a characteristic metamorphism;
- 3D geometry of deformations (in plan and cross-section): types of the structures, their vertical and lateral rows, oroclinal bends;
- correlation of the arc-continent collision orogenies in a context of global tectonic cycles and phases.

III. The Conditions of the Process

The necessary condition of a collision of an island arc and opposite continent is an oceanward dip of a subduction zone (from a continent to an ocean) (Fig. 2). Island arc will never collide with an active continental margin. The margin is always passive. The preservation of such a geodynamic situation leads to a complete disappearance of an oceanic crust, dividing the passive continental margin and the island arc, and therefore a thinned part of the margin is involved into the subduction zone – until the moment when the buoyancy of the continental lithosphere exceeds the driving force of the subduction, so the subduction is jammed.

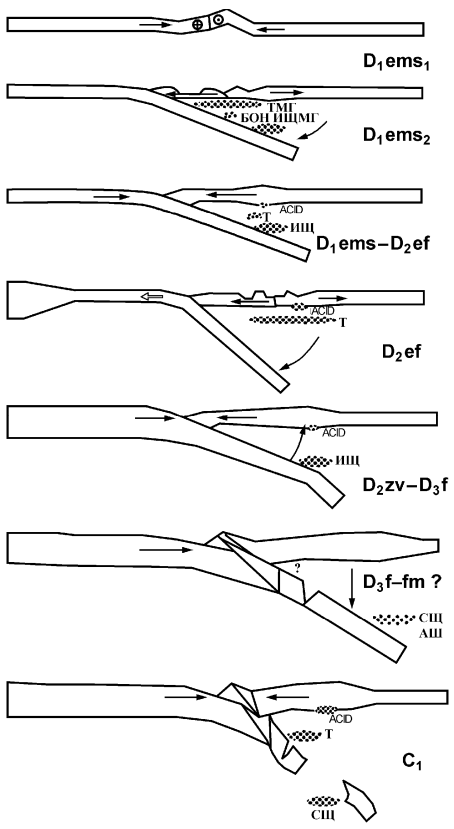

Fig.2. A model for development of the Magnitogorsk arc and subduction zone [8]. Dotted lenses, supposed zones of melting of initial magmas of different petrogenetic types: T, tholeiitic; BON, boninitic; TMg, tholeiitic magnesial; CA, calc-alkaline; ASh, absarokite-shoshonite; SA, subalkaline. Stages of the Devonian: em, Emsian; ef, Eifelian; gv, Givetian; f, Frasnian; fm, Famennian. C_1, Lower Carboniferous

It must be also taken into account that the buoyancy of an ancient continental lithosphere is usually higher than that of a younger continent, because the ancient mantle, “frozen” to a craton, is very depleted and lacks sufficient volumes of dense eclogites [1]. That is why the most bright examples of arc-continent collisions are connected with cratons or their fragments, reworked by a later diastrophism. Such are collisions of Sunda arc–Australia, Bigger Antilles–Florida, Tyrrhenian arc–Gondwana, Newfoundland Ordovician arc–North America, Australian craton–Macquarie arc and others. In the Urals a distinct episode of an arc-continent collision took place in the Late Devonian-Early Carboniferous, when the Magnitogorsk island arc collided with Balica craton, incorporated into Laurussia continent [2, 3].

The theoretical approach to the problem of arc-continent collision includes two main aspects: ***historical*** and ***geometrical.***

IV. Historical Approach

A. Collision time reflected in a sedimentary process

Under certain conditions, the process of subduction is accompanied by a formation of an accretionary complex [6], a chaotic structure of mélanges and thrusts, formed by a bulldozer-like action at the front of a subduction zone.

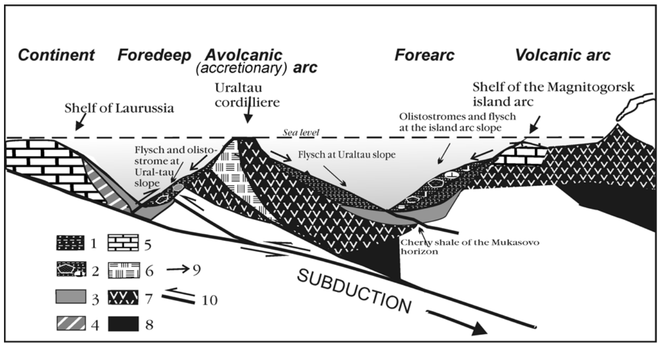

Fig. 3. A reconstruction of the collisional structures for the Famennian of the Southern Urals. 1 – Zilair flysch, 2 – olistostromes, 3 – cherty preflysch, 4 – bathyal (O–D_2) deposits, 5 – shelf deposits, 6 – Maksyutovo HP-LT metamorphic complex, 7 – island arc volcanics, 8 – ophiolites, 9 –directions of a terriggenous transport, 10 – faults and directions of tectonic movements

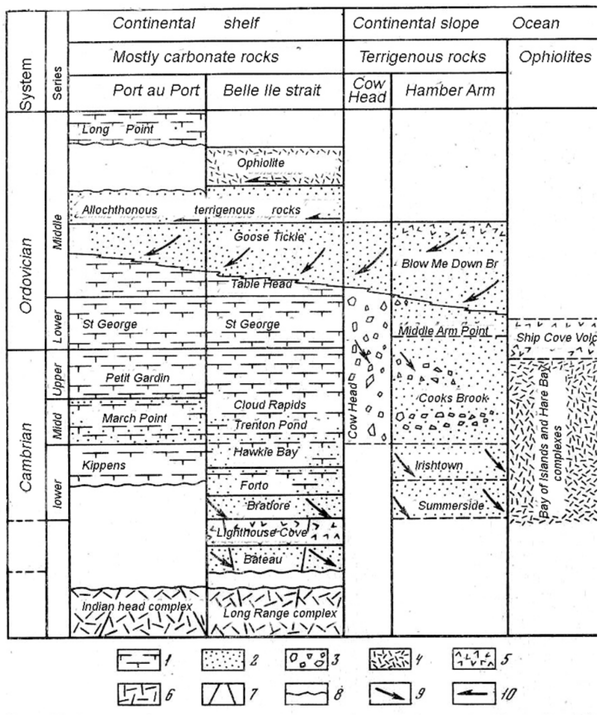

Fig. 4. Western Newfoundland by the beginning of the Taconic deformation [12]. Rocks: 1- carbonate, 2 – terrigenous, 3 – deep-water carbonate breccia, 4 – layered plutonic, 5 – basic volcanic, 6 – metamorphic, 7 – basic dykes, 8 – unconformities, 9 – direction of a terrigenous transport, 10 – tectonic boundaries under allochthons.

In many cases, like with the Sunda (Fig.1), Mariana and some other arcs, the complex is high enough to form an avolcanogenic arc, a source of a terrigenous polymictic material wich is shed in both interarc and forearc depocentres.This situation is aggravated during collision, when the arc becomes pressed agaimst a slope of a passive continental margin, and a bulldozer effect of a rigid volcanic part of the arc develops in a full mesure. Terrigenous material, as a greywacke flysch formation, reaches a bathyal, and then a shelf zone of the passive margin, clearly showing that collision is here [3,7,8]. In the Southern Urals, this event is marked by a formation of Famennian Zilair greywacke flysch (Fig.3); in the Polar Urals the analogous event comes later: the first greywacke (Jayu formation) appears only in the Early Visean [9].

Both formations are dated by fossils. The change of the provenance is additionally approved by mineralogical analysis of greywacke [10] and a mass laser ablation dating of phengite in it [11]. In the western Newfoundland, according to [12], greywacke of the eastern provenance come in the Mid-Ordovician (Goose Tickle and Blow Me Down formations) (Fig.4). In both cases, subduction was not finished, but shifted to more internal parts of corresponding paleo-oceans.

B. Characteristic metamorphism and its age

It is generally accepted that collision is often accompanied by a HP-LT eclogite-glaucophane metamorphism. Its products are being formed at great depths of 70-100 km as it is shown by their mineral equilibria. Therefore the rocks must be quickly exhumed back to the surface by some process which is still rather enigmatic. The author thinks that the most probable mechanism is connected with a buoyancy of a continental margin or its fragment, originally transported by subduction to great depths [13,14].

The HP-LT complexes are not always well exposed at the suture zone between the continental and island-arc terrains. In Taiwan, they are present only as blocrs in the sedimentary Lichi mélange [15], and their isotopic age is still not determined. In the Australian Tasmanides, blueschists, presumably corresponding to a collision of a Cambrian arc in the Early Ordovician (Delamerian orogen) and an Ordovician arc – at the boundary of the Ordovician and Sulurian (Lachlan orogen) are situated in the back of the zone of development of the island arc formations, owing to high-amplitude thrusting of island arc complexes to the west from their suture [16]. On the contrary, in the Urals [7], they form a 2000-km discontinuous belt, the longest in the world, just in the contact with massive relics of the corresponding Paleozoic arc (Fig.5).

In the Urals, the data on the first appearance of greywacke flysch are consistent with the most part of the isotopic dates for the eclogite-glaucophane complexes: In the Southern Urals it is the Frasnian-Famennian, in the Polar Urals – the Early Carboniferous. However it is necessary to point out that the whole range of U-Pb (zircons), Rb-Sr, Sm-Nd and Ar-Ar dates for the metamorphic rocks encountered at the suture of the Main Uralian Fault (MUF) includes also much older dates (even Precambrian), as well as much younger ones. The problem is that even Ar-Ar dates which are declared to date the end of exhumation and a final closure of isotope system in phengites of glaucophane schists correspond to a 350-370^{o} C isotherm [17], which means a depth of ca. 10 km. It is much shallower than initial 70-100 km, but still not the surface. The further way of the complexes to the surface is traced by Ar-Ar dates after muscovites and by a fission-trek analysis (Carboniferous and later). The upper time limit of the appearance of eclogites of the Southern Urals to the surface is set by the fact of their transgressive contact with marine Upper Cretaceous deposits with fauna.

But more realistically the end of collision in the Southern Urals is dated by the Lower Carboniferous contrast eruptive and intrusive magmatism and dolerite dyke series in the Magnitogorsk arc, which have within-plate (rift) chemical characteristics and can be connected with the slab breakup and formation of a slab window, giving an access to deeper melts [8].

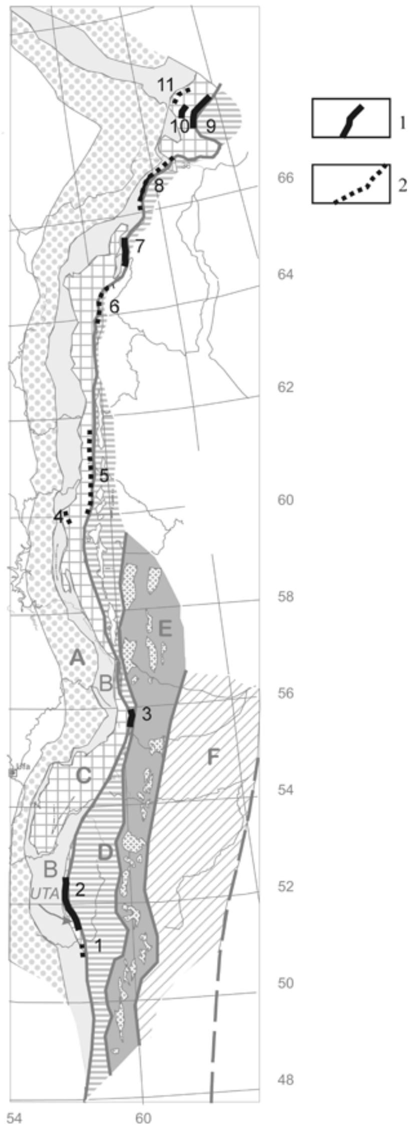

Fig. 5. HP-LT metamorphic belt of the Urals, superimposed on its tectonic map [8]. 1 – eclogite-glaucophane and eclogite complexes: 2 – glaucophane schists. Number 2 in the scheme – Maksiutovo complex (cf. with Fig.3)

V. Geometrical (Structural) Approach

A. Collisional structures in a cross-section

The deformations in the footwall of the major thrust dividing the continental and island-arc terrains, demonstrate some stable patterns. Collisions are accompanied by an origin of a series of continentalward-vergent thrust sheets. Their formation is subjected to strict regularities of a critical wedge theory and model [18,19]. The model is universal: it can be applied to a single sheet, an accretionary prism, a fold and thrust belt and even a whole orogen [20]. According to it, the geometry of the deformed wedge at the foreland margin ahead of a rigid buttress ("backstop") is a result of a balance (dynamic equilibrium) between gravity and compressional forces, frontal offscraping, underplating, thrusting, folding and erosion. As a result, in a process of deformation, new thrusts form in the front of the wedge and every next thrust sheet underlies the previous, forming a regular sequence. The model explains very well the origin of a "thin-skinned tectonics", typical for many forelands, where the whole thrust sequence is underlain by a gently dipping detachment surface, and the older thrusts overly the younger ones. In more general scale, such a mechanism may also explain a formation of regular "nappe stratigraphy", where all thrusts are subjected to the rule: "the higher, the older". On the other hand, the wedge is not always pushed by a backstop: according to many seismic studies, thrust structures are subjected to variations, forming a lateral row. In this row, "thin-skinned" tectonics changes inwardly across a ramp to a "thick-skinned" tectonics with much more steeply dipping thrust surfaces. In its turn, this type of the structures may be changed by a "squeeze and crush" tectonics of a suture zone with their structures of a plastic flow and mèlanges. [8].

The arc-continent collision may be accompanied by an obduction of ophiolite massifs (Kraka massif in the Urals, or Semail in Oman). The obduction is not independent process: the forces for thrusting of mantle sheets onto a passive margin are provided by a collision. It can be shown that an obducted ophiolite sheet formed firstly as a thrust over pelagic sediments. In its turn, the pelagic sheet is thrust over a continental shelf, and only after that, the thin-skinned tectonics develops in the shelf sediments [21]. In the process of a thrusting of a hot ophiolite sheet, a metamorphism in the footwall of the thrust is possible, as in Oman, Northern Appalachians and Newfoundland. But such a type of metamorphism is not found in the Urals, though some attempts were made. In particular, amphibolites and granulites in the exocontacts of the Khabarny mafic-ultramafic massif in the Southern Urals were attributed to an obduction of it over the margin of Laurussia continent [22]. However the age determinations of different members of this massif (Upper Silurian and Lower Devonian give no chance to neither collisional nor obductional interpretations, leaving place to some different suggestions [8].

B. Collisional structures in a plan

Usually the plate tectonic movements and deformations may be approximated in plan by Euler theorem. His theorem of a "fixed point" states that any movement of a rigid body at a sphere surface can be represented as its rotation around a specific pole. The theorem is widely used for a description of movement of rigid lithospheric plates. However an island arc (with underlying lithospheric slab) often behave as a plastic body. They are easily deformed and in certain cases are oroclinally bent in plan (e.g. Ambon arc – the eastern flank of Sunda arc – under collision with a protruding edge of Australia continent (Fig. 1). In such cases the positions of Euler rotational poles even for close neighbour parts of the arc are not the same, changing incrementally from one place to another. Therefore the early version of lithospheric plates as absolutely rigid bodies, needs some corrections.

A special case is represented by a Carpatian arc, with a backarc basin which was not opened as oceanic, but just rifted and stretched, preserving a thinned continental crust. At that, paleomagnetic studies prove its oroclinal bend in plan, after the Cretaceous time [23]. Probably the arc collided with the continent before it could completely develop.

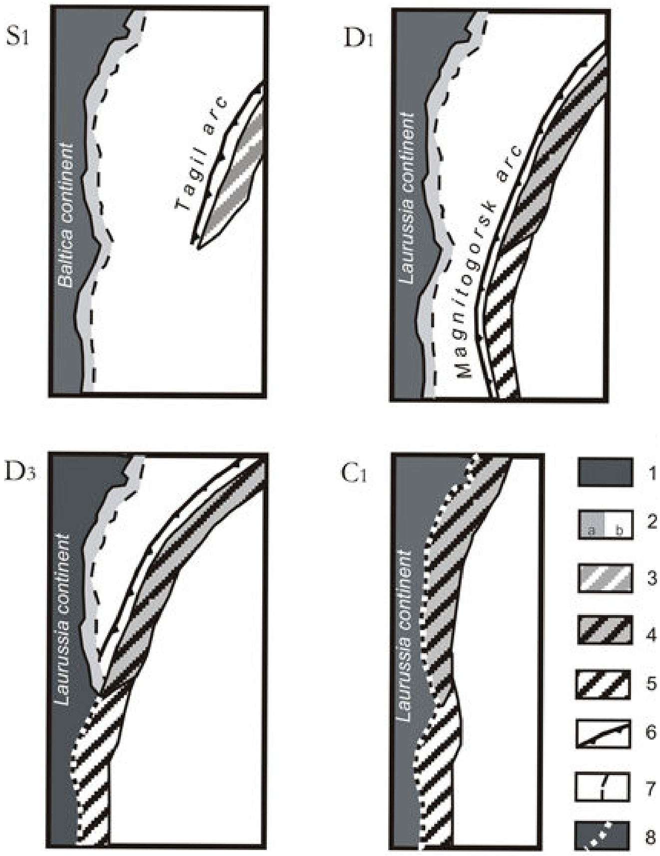

Fig. 6. A step-wise collision of the Magnitogorsk arc and Laurussia continent in the Devonian (D_1,D_3) and Carboniferous (C_1). 1 – continental crust; 2a — transitional crust; 2b — oceanic crust; 3 — Tagil island arc; 4 and 5 — Magnitogorsk island arc: 4 — ensialic (epi-tagilian), 5 — ensimatic (Magnitogorsk arc *sensu stricto*); 6 — subduction zone; 7 — continent – ocean boundary; 8 — suture zone.

Of a special interest is also a problem of formation of Kazakhstania continent in the period of Devonian-Carboniferous. According to [24], The Kazakh foldbelt as a part of Altaids, was formed from a Kipchak arc. Some corrections to this idea came from new paleomagnetic data [25]. It was shown that the Devonian ensialic arc (or rather narrow band-like continent with a subduction zone under it), experienced in the Carboniferous time a colossal oroclinal deformation, acquiring a horseshoe appearance in plan. The direction of bend was opposite to what had been shown in [24] and was conditioned by a narrow space between Siberia and Laurussia continents, colliding with Kazakhstania.

In fact, an arc usually does not collide with a continent at its whole length. An arc outline is as a rule not complementary to an outline of an opposite continent, with its promontories and recesses. In addition, it often happens that an arc and a continental margin are strongly unparallel, and collision becomes oblique.

At its first approach, the arc touches the continent with only one side; the other is left free. As a result, a triangular oceanic gap (TOG) is formed, which potentially can be closed somewhat later (Figs.1, 6). It was exactly what happened with the Magnitogorsk island arc, which collided with Laurussia continent in the Southern Urals by the Late Devonian, and in the Polar Urals by the Early Carboniferous [3]. The same situation demonstrate Luson arc (Taiwan), Bigger Antilles, Sunda arc and others. However in some cases an arc can collide with two continental masses. Such cases can be called a "narrow space tectonics". A good example of such a situation is a tectonics of a Tyrrhenian arc, squeezed and bent between African and Apulian blocks of Gondwanan origin.

VI. Conclusion

The discussion of peculiar features of arc-continent collisions leads to one more theoretical extension. The orogenies, connected with collisions of this type (like most of orogenies in general [26]), are not following a strict global rhythm. Notwithstanding a general cyclicity of tectonic processes (assembly and break-up of supercontinents, manifestations of Wilson cycles), individual collisions and their orogenies are not global but rather random: they have quite long duration (many Ma) and are strongly subjected to local conditions, such as outlines of continents, oblique orientation of subduction zones, and in general – a specific, individual geometry of collision.

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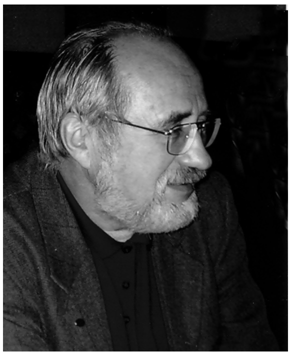

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