Ancient Urals — New Problems

by Aleksandr M. Dymkin and V.N. Puchkov

The Ural Mountains have long been regarded as a classical geosynclinal region. However, recent studies on Uralian ophiolites, melanges and deep-fault structures together with seismic profiles and drill-hole data lead to interpretations involving plate tectonic models. In this paper the authors review the overall structure, stratigraphy and evolution of the Urals.

Introduction: Fixism vs Mobilism

The Ural region (Fig. 2) is one of the oldest mining areas of the world; with very large mineral reserves it is the base of the powerful Soviet industry. Extending north to south for over 2000 km, this range contains folded, magmatic and metamorphic rocks from Archaean to Mesozoic in age. It was in the Urals where Murchison first distinguished the Permian System, and it was here that the stratotype was proposed for the Riphean by N.S. Shatsky. The Urals also provided the material for the fundamental works of A.P. Karpinsky, A.N. Zavaritsky and D.V. Nalivkin. A.V. Peive's concept of deep faults and D.S. Korzhinsky's of metasomatism arose from their work on the Urals, and the Soviet approach to the analysis of formations (N.S. Shatsky and N.P. Kheraskov) began here.

In the last decade or so, two distinct concepts, fixist and mobilist, have been vigorously applied to the Urals. The fixist view in its most complete form was set forth at the beginning of the 1970s by A.A. Pronin (1971) and I.D. Sobolev (1968) among others. According to them a number of cycles (Baikalian, Caledonian, Variscan) can be seen in the evolutionary history of the Urals. Each cycle began with the break-up of a stable zone and geosynclinal subsidence, allowing the accumulation of thick sequences of sediments and followed by active volcanism, injection of intrusive rocks and metamorphic processes. Each cycle ended with intense folding, synchronous with movements in other regions and destroying the geosynclinal trough. Temporary stabilization followed until the beginning of a new cycle. The tectonism that caused the formation of geosynclinal zones of subsidence and their annihilation was considered to be the result of vertical movements of crustal blocks separated by subvertical deep faults.

The fixist concept seemed quite secure until the late 1960s when the new ideas of lithospheric plate tectonics began to attract attention throughout the geological world. In this mobilist view, the lithosphere is divided into a number of large plates, which move horizontally relative to one another. Where they diverge in regions of tension along mid-ocean ridges, thin heavy ocean crust is formed. Where they converge in regions of compression, island arcs and volcano-plutonic belts marginal to the continents form, the crust thickens, and light silica-rich material accumulates to build the continents.

Although the plate tectonic concept arose from study of the geology of oceans, it soon influenced ideas on the geology of the ancient folded regions of the continents. Among the first geologists to apply these new ideas were those working on the Urals. An important stage in this work was the creation of a 1:1 000 000 tectonic map published together with an accompanying explanation in 1977 (Peive *et al.*). This work was

Figure 1: The valley of the Truba-iu River in the Voykar ophiolite massif of the Polar Urals.

carried out by the Geological Institute of the Academy of Sciences of the U.S.S.R., the Institute of Geology and Geochemistry of the Ural Scientific Centre and the Geological Production Association "Uralgeologiya" under the guidance of A.V. Peive and S.N. Ivanov.

Brief Outline of Ural Evolution

Our own view is that at the beginning of the Palaeozoic a continent existed in place of the contemporary Urals. In the Ordovician this continent broke up to form two lithospheric plates moving apart from one another. In the ocean basin that was born between these plates, ophiolites appeared — a stable association of heavy deep-seated rocks depleted in silica (dunites, harzburgites, pyroxenites, gabbroids), a series of diabasic dikes with basaltic lavas, and deep-water sediments (cherts and less commonly limestones). These ophiolites are now best developed on the eastern slope of the Urals within the so-called Zelenokamennaya zone.

In the Silurian there appeared, for the first time within this oceanic depression, extensive calc-alkaline rocks and a variety of shallow and deep-water sediments and tuffs. All these geological formations, including plagiogranites and related rocks, can be readily compared with those in contemporary island arcs. In the Silurian and Devonian, zones of island arc rocks divided the primary oceanic basin into a system of ridges and deep-water troughs, filled with thick sequences of sediments and subordinate volcanics. Throughout this period the light material forming the new continental crust continued to accumulate.

The decisive moment in the development of the continental crust of the eastern Urals was the beginning of strong compressive orogenic processes, which became intensive in middle Carboniferous time, continuing in intervals up to the Triassic. Folding in the Urals was followed by a considerable reduction in the widths of the geosynclinal troughs, by the formation of nappes and huge batholithic granites, and by the thickening of the crust. The result was to unite the colliding lithospheric plates into the uniform platform of Northern Eurasia.

Figure 2: Tectonic Map of the Urals. Unpatterned area to west is the East European Platform. Arrows with numbers show locations of other figures in this paper. For further explanation see text.

The Ophiolites of the Eastern Urals

Ophiolitic associations are extraordinarily abundant in the Urals, and one of the central questions now being solved concerns their petrology, structure and genesis – a matter of global importance. A very interesting problem here concerns the inner structure of thick ultrabasic massifs (Fig. 1). According to the view first proposed by S.V. Moskaleva in the 1960s, the large dunite-harzburgite bodies of the Urals such as Syum-Keu, Rai-Iz, Voykar and Kraka represent large masses detached from the mantle and containing relics of its structure (for recent reviews in English see Savelyev and Savelyeva, 1977, and papers by Ivanov et al., Ruzhentsev and Saniygin, Savelyev and Savelyeva, and Lennikh et al., in Malpas and Tallington, 1979 – Ed.). This concept received much stimulus from the work of A. Nicolas and his colleagues (1973). Studying the structure of these massifs thus reveals something of the stages of development of the Palaeozoic oceanic mantle in the Urals (Savelyeva and Denisova, 1983).

In the popular magmatic-mantle hypothesis, ophiolites are viewed as forming close to the axial part of the mid-ocean ridge in a magma chamber established on a dunite-harzburgite substratum of the mantle. Constant crystallization and

differentiation take place as the melt cools. The crystals that appear settle to the bottom to form layers of different composition, mainly dunites, pyroxenites and gabbroids. Diabasic dikes cut the upper part of the gabbroid layer, locally forming continuous complexes of parallel dikes, which testify to stable processes of tension. Further upwards in the section, the dike complex changes into a sequence of basaltic lavas intercalated with deep-water sediments. This hypothesis fits well with plate tectonic concepts of lithospheric platforms, and contributes to comparison of ocean bed formations and to formations of folded continental belts. It also explains the succession of rock formations observed in modern ophiolitic belts.

However, this concept also has its drawbacks. Geophysicists have not found such large magma chambers under modern mid-ocean ridges. It is also rather difficult to estimate the composition of the parent magma, which could have given birth to the layered complex, for there are no analogs to this magma in volcanic rocks of the modern oceans. Ophiolitic sections both in the oceans and on the continents by no means always exhibit the standard succession described above; in particular the dike complex is quite commonly absent. Where present, it usually contains blocks of the underlying rocks, which it had intruded; these older rocks are generally represented by ultrabasics and gabbroids, which were metamorphosed, and deformed and cooled prior to the period of dike intrusion. The rocks of these layered complexes commonly exhibit metamorphic features such as granoblastic texture and stability of composition, insofar as the chemical composition of their minerals is independent of their abundance.

These and other considerations have led to a new hypothesis for the genesis of ophiolites (Yefimov and Puchkov, 1980). Comparison of the composition of the Ural ophiolites with fragments of the relatively deep mantle, which occur as inclusions in alkaline

basalts, indicates clearly that the upper mantle contains not only high-magnesium ultrabasics, but also rocks with a chemistry comparable to that of Alpine-type ophiolitic gabbroids, despite the gross differences in the composition of their minerals. Gabbroids cannot however exist at great depths, and their high-pressure equivalents here are garnet pyroxenites and eclogites. These considerations led Yefimov and Puchkov to suggest that ophiolites originate under mid-oceanic ridges from ductile, high-temperature, basic-ultrabasic material rising from deeper portions of the upper mantle, followed by fusion of oceanic basalts.

Undepleted basic-ultrabasic material of the mantle (pyroxenite) separates at depths of 20–60 km into basaltic magma and a complex refractory residue composed of dunite, harzburgite, eclogite and garnet peridotite. As this mantle material rises to lower pressure zones, the eclogites and garnet peridotites change into gabbroids, blocks of which, being much lighter than the other mantle rocks, rise to accumulate as the lower layer of the oceanic crust. Meanwhile deeper in the mantle, oceanic basalts originate by the fusion of undepleted mantle material. They rise to the surface to form the volcanic layer, which is then overlapped mainly by deep-sea sediments.

Figure 3: Panoramic view in the northern Urals. Broken line shows unconformity between Riphean and Ordovician. Cambrian rocks are absent here.

This hypothesis is in accordance with the well-known geophysical models that view the convection of magma as the cause of movement of lithospheric platforms. However whether this concept or the mantle-magma hypothesis is correct, only further critical study will decide.

Palaeozoic Sediments of the Western Urals

Recognition of the oceanic nature of the Palaeozoic troughs of the eastern Urals is an important factor in plate tectonic interpretations of this mountain region. The Palaeozoic sediments of the western Urals were considered to be wholly geosynclinal, in contrast to the sediments of the East European platform to the west. These sediments were thought to have undergone Caledonian folding in the Ordovician and/or Devonian to cause the appearance of the Central Ural Uplift, the erosion of which from time to time supplied terrigenous material to the west. However, thorough facies and palaeotectonic analyses show that throughout much of the western slope of the Urals (within the limits of the Belsko-Eletskaia structural-facies zone), shallow water sediments were deposited in the lower and middle Palaeozoic under similar conditions to those existing in the adjacent platform, and that gently sloping platform structures with non-Ural orientation were formed. Not until the end of Palaeozoic time did these rocks undergo intense folding along Uralian trends, and it was at this time that the Central Ural Uplift appeared (Fig. 3, and Puchkov, 1975).

The interpretation of the deep-water Palaeozoic sediments of the western slope of the Urals within the Zilairo-Lemvinskaya zone is of equal importance. These terrigenous sediments consist of interbedded sandstones, siltstones, argillites, limestones, and cherts, ranging in age from Ordovician to Lower Permian, and found in erosional-tectonic remnants throughout the western Urals. Their deep-water character is indicated by the pelagic character of their fossil fauna, their peculiarities of geochemistry and lithological composition, and in particular by the presence of turbidites characteristic of modern continental margins.

Until the recent discovery of conodonts, the extreme paucity of fauna was a principal difficulty in unravelling the geological history of these rocks. Analysis of these organic remains has led to radical changes of the views on stratigraphy of these deposits (Fig. 4). For example, it is now recognized that all the divisions of the Devonian are represented in the Zilairo-Lemvinskaya zone, where previous workers had placed a major erosional hiatus at the base of the Carboniferous sediments, and where only Ordovician, Silurian or Carboniferous rocks were thought to occur

Figure 4: Searching for conodonts in Palaeozoic bathyal cherts.

(Fig. 5). Thus the last arguments in favour of the prolonged development of the Central Ural Uplift disappeared. On the western slope of the Urals, the relicts of a Palaeozoic passive continental margin can clearly be seen as Ordovician-Devonian sediments of neritic and bathyal regions (Puchkov, 1979).

The question of the primary character of the junction between western sediments and the eastern rocks of the palaeo-oceanic region of the Urals has not, however, been solved, for they are now separated by a deep fault zone described below. Nevertheless present-day workers tend to distinguish in the Urals geological assemblages corresponding in composition and lithology to the complexes of modern oceanic basins and island arcs, and to the shelves, slopes and rises of modern passive continental margins. Yet, the width of the Urals does not exceed 300 km, and the Ural geosynclinal trough must have undergone at the end of its development a considerable reduction in lateral dimensions. The evidence for such movements can be found in nappe structures.

Lateral Shortening: Nappes and Island Arcs

As early as the 1930s and 1940s, nappe structures were identified by G.N. Frederix, E.A. Kuznetsov, A.D. Arkangel'skiy, K.G. Voinovskiy-Kruger and many others. These interpretations were, however, overshadowed from the early 1940s by fixist concepts of the Ural structure, and it was not until the 1960s that the idea of the wide development of nappes in the Urals was restored as a result of new structural-facies analyses, and geophysical and drill-hole data (e.g. Kamaletdinov, 1974; Ruzhentsev, 1976).

One of the largest nappes, the Malopechorskiy, was identified in the northern Urals; new evidence was presented for the nappe structure of Lemvinskaya zone of the Polar Urals (Fig. 6), and the inner structure of Bardymskaya nappe of the Middle Urals was described (Puchkov, 1979). The latter nappe, first described by O.A. Neiman-Permyakova and G.A. Smirnov, is of special interest for its existence was proved by data from five structural holes drilled into the Ordovician-Devonian deep-water, terrigenous to cherty sequences comprising the overthrust sheet and the Devonian shallow sediments of Belsko-Eletskaia zone, which underlie this nappe. The minimum lateral displacement of the Bardymskaya nappe is regarded as about 30 km.

Figure 5: The "Middle Gates" of the Schugor River, western slope of the Urals. The cliffs are of Carboniferous limestones which represent the upper part of the section of deformed Palaeozoic shelf sediments. In the background are low outcrops of Lower Permian flyshoid sediments.

Figure 6: Intensely deformed Riphean metamorphics with typically flat-lying schistosity, Khobeis dome, eastern slope of the northern Urals.

Nevertheless, the nappe tectonics of the Urals and especially its eastern slopes are not yet fully understood. The fundamental question of the width of the Palaeozoic oceanic basin still remains, with some workers comparing it to the width of the Atlantic Ocean, others to the Mediterranean Sea, and some to the Red Sea rift.

The existence of island arcs in the development of the Urals may provide circumstantial evidence of considerable lateral crustal shortening. According to the subduction model, the zones of deep-focus earthquakes, located under the modern island arcs and active continental margins, mark the surfaces on which one lithospheric plate constantly moves under the other, partly remelting and partly being absorbed by the mantle. Strong compression of the Urals in the late Palaeozoic caused the disappearance of the island arcs as such, but there remain thick complexes of calc-alkaline, basaltic, andesitic, dacitic and other magmatic rocks, with relicts of volcanic structures which mark axial volcanic zones of these island arcs. There are also welded tuff and tuff-turbidite sequences with jasperoid horizons which correspond to the slopes of island arcs.

The interpretation of these complexes, their primary lateral distribution, and their relations with the underlying oceanic and overlying flysch sequences is not yet complete because of the lack of stratigraphic data. Recent discoveries of widespread conodonts in cherts will, however, assist in the successful solving of many stratigraphic problems. The correct interpretation of geodynamic history, of course, is not possible without a firm stratigraphic basis.

Paired Metamorphic Belts

The possible existence in the Urals of "twin" or paired metamorphic belts may help to establish indications of subduction zones. These were first established in the Japanese island arc (Miyashiro, 1973) where folded zones of the Pacific Ocean margin commonly contain parallel metamorphic belts of nearly the same geological age but contrasting character. One of these belts usually corresponds to the low or moderate pressures and high temperatures of the amphibolitic facies, and the other to the high pressure and relatively low temperature eclogite and glaucophane-schist facies. Such paired belts are regarded as corresponding to zones of collision between lithospheric plates, the high pressure belt being formed at the front of island arcs close to the sinking cold oceanic platform, and the high temperature belt behind the island arc.

The work of G.A. Keilman, V.I. Lennykh, N.A. Dobretsov, A.I. Russin and others shows that high-pressure metamorphic rocks are centered in a relatively narrow region along the Main Ural Deep Fault zone and to the west of it. High temperature Palaeozoic metamorphics (amphibolite facies) occur only to the east, within the Ural Zelenokamennaya belt and Uralo-Tobolskaya zone. At first sight this situation would seem to represent a typical twin belt of Palaeozoic metamorphism. However the matter is much more complicated, and the Miyashiro scheme does not fit here.

First, the amphibolite metamorphism of the eastern slope of the Urals did not develop everywhere at the same time. In the Zelenokamennaya zone it is mainly middle Palaeozoic, possibly coinciding with the island arc stage of development. However in the Uralo-Tobolskaya zone to the east, late Palaeozoic metamorphism is best represented, corresponding to the time of collision and tectonic piling-up of continental blocks.

Manifestations of eclogite and glaucophane schist metamorphism in the Urals are probably not of the same age and type either. In part, these metamorphic rocks developed at the expense of ophiolitic oceanic substratum, matching the phenomenon of subduction (cf. Miyashiro, 1973). However much of this high-pressure metamorphism has developed on rocks of the continental and intermediate crust within the Central Ural Uplift, regarded as a passive continental margin during the middle Palaeozoic.

One hypothesis, therefore, is that Palaeozoic (and Precambrian) metamorphic rocks of the Urals belong to at least two twin belts of different genesis. The first (middle Palaeozoic) is obviously related to underthrusting of the oceanic plate to the east under the island arc; the other (late Palaeozoic) is associated with the collision of two continental blocks during the final closure of the geosyncline.

The Main Ural Deep Fault

The new interpretations of the geology of the Urals requires a revision of ideas on deep faults, a very popular concept in the U.S.S.R. One of the tectonotypes for these is the Main Ural Deep Fault (MUDF), which separates the western palaeocontinental from the central palaeo-oceanic regions in the Urals.

The MUDF appears to have formed under conditions of tension, bordering the newly formed oceanic crust. Its

primary nature has, however, been obscured by later deformation related to the lateral compression of the Uralian geosyncline. It is not surprising therefore that the MUDF is associated with high pressure metamorphism; exposures of blastomylonites of amphibolite and greenschist facies mark its deep-seated portions.

A large part of the extensive Uralian zone of serpentinite mélange is confined to the MUDF zone, where it is represented by gigantic tectonic breccias composed of heterogeneous, sometimes exotic, fragments in a ductile serpentinite matrix. As shown on Figure 1, the Sakmaro-Voznesenskaya mélange zone, which extends along the southern segment of the fault, passes northwards into the Serovsko-Maukskaya zone, which is in turn overlapped by Meso-Cenozoic sediments of western Siberia. Together these two zones form one of the world's longest (more than 1200 km), generally unbroken, zone of mélange development, the northern and the southern terminations of which are unknown.

According to recent seismic data, the surfaces bounding the MUDF zone dip to the east at rather high angles (40-60°). However, there is reason to suppose that they flatten out with depth, like the surfaces of many nappes studied by drilling. Considerable overthrusting probably occurred along these surfaces in the Palaeozoic, together with the consumption of a great amount of crust. As a result, extremely varied rocks, originally of far distant facies, have been brought into juxtaposition and whole facies zones obliterated. Similar structures outside the Soviet Union are now generally labelled "suture zones" (e.g. the Himalayan Suture Zone of Gansser, 1980). Thus, the fixist concept of deep faults finds its place in the new tectonic models of the Urals.

Finally, there is the problem of the deep crustal structure of the Urals. There has been much geophysical study of the Urals in the last two decades, geophysical anomalies have been thoroughly investigated and their interpretation attempted. Many seismic studies have been carried out, including several profiles of deep seismic sounding. As a result, the crust beneath the Urals is now considered to be 40-50 km thick and grossly differentiated in its structure. Within the limits of Tagilo-Magnitogorskaya eugeosynclinal zone the crust is thick, heavy, and "simatic," with a reduced "granitic" layer. The granitic layer is however much better developed in the Zapadno-Uralskaya and Uralo-Tobolskaya megazones, the former being characterized by sialic crust, the latter being heavy, heterogeneous and combined with light blocks.

Conclusion

The conclusion that the Uralian crust in the Palaeozoic evolved from oceanic to continental under conditions of compression and tectonic piling-up leads to the supposition that the modern crustal profile may commonly be doubled and tripled in thickness, with old continental blocks locally overlapped by plates of the oceanic crust. However while modelling the deep structure of the Urals, there is still enormous space left for the imagination. Moreover, drilling of the Kola Super-deep well (see Kozlovsky, 1982, - Ed.) has thrown doubt on standard geophysical models of deep crustal structure. Drilling of a new superdeep well (to 15 km) planned for the Central Urals near Krasnouralsk, should give a real geological dimension to the available profiles of deep seismic-refraction.

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