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Mesozoic–Cenozoic metallogenic provinces, Wilson cycle, and plume tectonics

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Abstract. The aim of this paper is to discuss the association of the major Mesozoic and Cenozoic provinces (metallogenic belts and oil–gas basins) with the Pangea breakup and mantle plumes. Assuming that the large plumes did not change substantially their positions, their modern projections to the Earth surface can be applied to the whole of this period of time. From the end of the Paleozoic through the early half of the Mesozoic (early stages of the cycle) the Indian–African Superplume controlled the formation of rift systems along the lines of the future breakup of the supercontinent. This activity was accompanied by trap lava flows, the emplacement of layered basic intrusions and granites of high alkalinity with the formation of Cu–Ni and Pt mineralization, and the formation of rare-metal and rare-earth ore deposits. The belts of low-temperature and telethermal ore deposits, as well as large oil and gas pools, were formed along the peripheries of this and other superplumes. During the end of the Jurassic and the beginning of the Cretaceous (middle phases of the cycle) young oceans began to open with the divergence of the continental blocks. Simultaneously, rifting activity continued above the hot plumes along with the associated magmatism and mineralization. Active continental margins with rare metal and copper pyrite mineralization developed beyond the plume projections in the northern part of Tethys and at both sides of the Pacific Ocean. At the end of the Mesozoic and during the Cenozoic the breakup and divergence of the last fragments of Pangea took place in Africa and Arabia and in Antarctica and Australia, although generally the leading role belonged to the processes of the convergence of continental blocks around Eurasia, the formation of subduction zones, and collision with the formation of the provinces of copper sulfide and rare metal mineralization. This trend characterized the closing phases of the Wilson cycle and resulted in the predominance of downward mantle flows over the upward ones, this mechanism causing the utmost reconstruction of the geodynamic and metallogenic characteristics over the larger portion of the Earth's lithosphere. Our analysis confirms that the metallogenic provinces had been formed as a function of the changes in the geodynamic conditions and as a function of their positions relative to the large plume projections. The items of open and closed plume systems and the zonal distribution pattern of the main metallogenic provinces above the hot plumes remain to be the matters of debate.

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1. Wilson Cycle and Geodynamic Conditions in the Lithosphere

The cycle of the formation and destruction of a supercontinent was suggested by J. Wilson in the early 1960s and was later named after him. This cycle includes the following successive stages: the convergence of continental masses with the closure of the oceanic basins separating them as

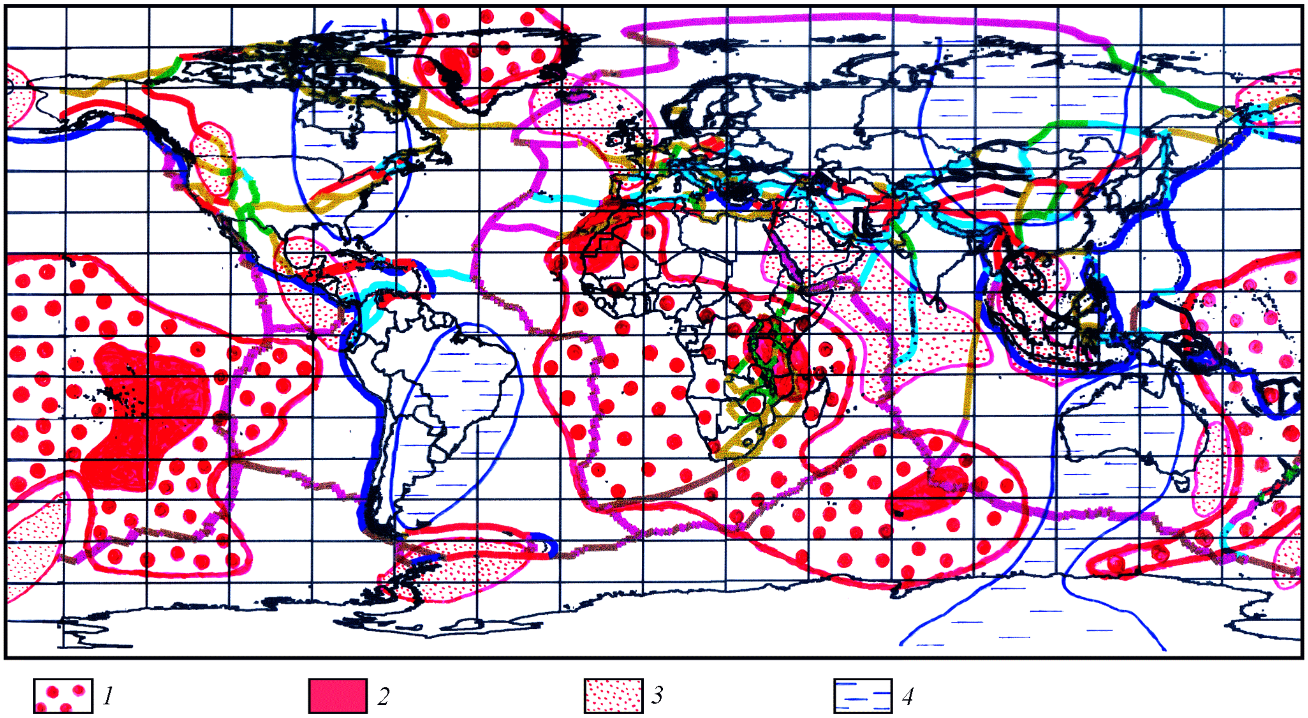

Figure 1. The map showing the projections of the major hot plumes and downgoing cold mantle flows onto the Earth surface. The spreading axis are shown in violet, the subduction zones, in dark blue, and the main fracture zones of various types, after the electronic geodynamic globe. (1) The superplumes located mainly in the depth range of 2900–1200 km; (2) "through" segments of superplumes (at all depth levels); (3) more shallow plumes (higher than 600 km); (4) the most persistent down-going flows of the cold mantle material.

the result of the predominance of the convergence and subduction of the lithospheric plates; their convergence into a large supercontinent as a result of the processes of collision, folding, and granitization; the breaking of the newly formed continental mass during a rifting activity with its breakup into individual continental blocks; the divergence of these blocks during the spreading activity and the formation of new oceanic basins. These cycles were repeated many times during the Proterozoic and Phanerozoic history of the Earth and are believed to have been associated with the transformation of single-cell mantle convection to multicell convection [*Khain,* 1995, 2001; *Sorokhtin and Ushakov,* 1993]. The last cycle began 250–300 million years ago and is still going on at the present time.

The Wilson cycles were accompanied by the alternation of oppositely directed geodynamic activities in the lithosphere. First of all, these were the replacements of the predominant compression and growth of the continental crust during the subduction and collision by its extension and disintegration as a result of rifting and spreading. Worthy of mention are also the transformations of extensive passive continental margins into active ones, the transformations of volcanic island arcs into continental-margin igneous rock belts, etc. These processes modified significantly the distribution of various metallogenic provinces and changed many of their characteristics [*Gatinskii,* 1985; *Khain,* 2000; *Kovalev,* 1985; *Mitchell and Garson,* 1981; *Rundkvist,* 1995]. Within the problem discussed in this number of the journal, it is of interest to trace a relationship between the various cycles of the Wilson cycle and the related mineral deposits with mantle plumes. But first, it is worthwhile discussing the modern ideas on the mantle plumes, their classifications in terms of size and depth, and the spatial association of various mineral deposits, combined into metallogenic belts or oil and gas basins, with the projections of plumes to the Earth's surface.

2. Hierarchy and Depth of Mantle Plumes and the Association of Mineral Deposits with Them

One of the most important achievements in the Earth sciences during the last decade was the discovery with the help of seismic tomography of large heat and density heterogeneities at various depths in the mantle and lithosphere. Their location was based first of all on the location of the regions of the slowdown and acceleration of seismic waves at various depth levels corresponding, according to the most widespread interpretation, to the hot ascending and cold descending flows of the material. The former are known as hot mantle plumes [*Dziewonski and Woodhouse,* 1987; *Kumazawa and Maruyama,* 1994]. It is significant that hot linear zones dominate at the most shallow depths (<200–350 km) under most of the active margins and continental rifts, whereas local isometric hot anomalies are observed at greater depths. Most of them concentrate in the central part of the Pacific Ocean and Africa and in the northwestern part of the Indian Ocean. Another important feature of the mantle plumes is the development of specific magmatism in the upper lithosphere above them [*Grachev,* 2000, 2002], represented by layered basic and ultrabasic intrusions, granites of high alkalinity and alkaline intrusive rocks, tholeiitic, subalkalic, and alkalic basaltoids, and contrasting volcanic rocks.

In our attempt to summarize and generalize the seismotomographic data from different depth levels and to map the most stable and large mantle structures from the results of deep seismic sounding, we mapped three major hot superplumes (Figure 1): the Pacific, the Indian–African, and the smaller Greenland superplumes, located mainly in the upper mantle in a depth interval of 2900–1200 km. These regions include areas of the almost continuous development of low velocities, the peculiar hot corridors rising from the boundary between the core and the mantle. They were recorded in the central part of the Pacific south of the Hawaiian Islands, in the area of the Kerguelan I., in East Africa, under the Canary Islands, and in the west of Greenland (except for the uppermost regions). Most of these regions are marked by Late Cenozoic and recent volcanic activity and high heat flow. The projections of the superplumes to the Earth surface are marked by many contemporaneous hot spots corresponding to the apophyses of the plumes at the higher levels of the mantle and in the lithosphere.

Relatively shallow (<600 km) hot plumes have been recorded also outside of the projections of the above mentioned large plums: under West Europe and Iceland, under Arabia and Near East, under Southeast Asia, and elsewhere. These plumes are usually interpreted as the far extending tongues of the superplumes. The most persistent downgoing cold flows, referred to as “cold plumes” by some researchers [*Kumazawa and Maruyama,* 1994], correspond primarily to the regions of the long-lasting subduction of the oceanic lithosphere under the continental plates.

Let us trace a relationship between the distribution of the major metallogenic provinces of late Paleozoic, Mesozoic, and Cenozoic ages and the above-mentioned superplumes. For this purpose we will use the schematic map presented in Figure 2, which shows the largest metallogenic belts and areas of these ages, the major oil and gas accumulation basins and the fields of ferromanganese concretions in the oceans, as well as the projections of the superplumes to the Earth surface. One can see that at the present time there is no regular association between the metallogenic provinces and the superplumes. However, one can see a principally different pattern when comparing the above mentioned metallogenic provinces with the individual stages of the last Wilson cycle beginning from the end of the Paleozoic. In this case we can see definite associations between some of them and their positions relative to the projections of hot superplumes which seem to have retained their general positions throughout the time period concerned [*Khain,* 1995, 2001]. For the analysis that follows, we will use the known palinspastic reconstructions of the positions of the continental blocks for the last 300–250 million years [*Scotese and Golonka,* 1992].

3. Early Wilson Cycle Phases: Late Paleozoic–Early Mesozoic

As follows from the geological data available and the palinspastic reconstructions mentioned above, the Pangea Supercontinent was wholly formed during the Late Permian–Early Triassic. The processes dominating in it were compression and the growth of the continental crust, yet, the early phases of rifting began and some indications of a future breakup were seen (Figure 3). These were the northward drift of the Sinobirmania–North Tibet microcontinent which began as early as the Late Carboniferous–Middle Permian [*Gatinskii,* 1986]; extensive trap lava flows in Eastern Siberia; rifting in the Kara Sea and Western Siberia; the emplacement of basic intrusions with copper–nickel and platinum mineralization in Norilsk (Eastern Siberia), South Africa (Insizwa) [*Mitchel and Garson,* 1981], Southern China and Northern Vietnam [*Poliakov et al.,* 1995], and also of high-alkaline granites with rare-metal and rare-earth ores in the Altai region [*Nechaeva,* 1976] and in the Oslo Graben.

Whereas the European and African magmatic areas were located within or near the Indian–African Superplume and the lines of the future Pangea breakup, the Siberian areas were notably remote from the nearest Greenland Plume. This is a surprising fact, because almost all of the subsequent trap lava flows (Figures 5, 7, 9, 10) were controlled undoubtedly by hot plumes and preceded the large breakups of the lithosphere in the regions of their occurrence. It appears that the enigma of the Siberian traps can be explained by the facts that our data for the Siberian tomography are still not complete, or that the paleoreconstructions available are not exact and that for the Early Triassic Siberia should be turned counterclockwise for a longer distance to be combined with the northern plume. It appears that later the rapid clockwise rotation of Siberia interrupted the beginning phase of this continent breakup. In any case, it is hard to agree with the view that Siberian traps flowed in the environment of dominating compression [*Migurskii,* 2002]. Most of the stratiform Pb–Zn and low-temperature Hg–Sb mineral deposits at the Pangea passive margins in North Africa, South-East Europe, and Arabia [*Mitchell and Garson,* 1981] were also controlled by the boundary of the Indian–African plume. Active continental margins with rare-metal and copper porphyry mineral deposits are known to have existed outside of the superplume projections in East Asia and East Australia (Figure 3).

Returning to the preceding Late Paleozoic epoch of oil and gas accumulation, one can see that several large basins that developed at that time (Figure 4) were also in or near the zone of influence of the Indian–African superplume. These are the basins of the Persian Gulf and North Sea during the early stages of their development, and also the Caspian, Midcontinent, and other basins. It appears that the high

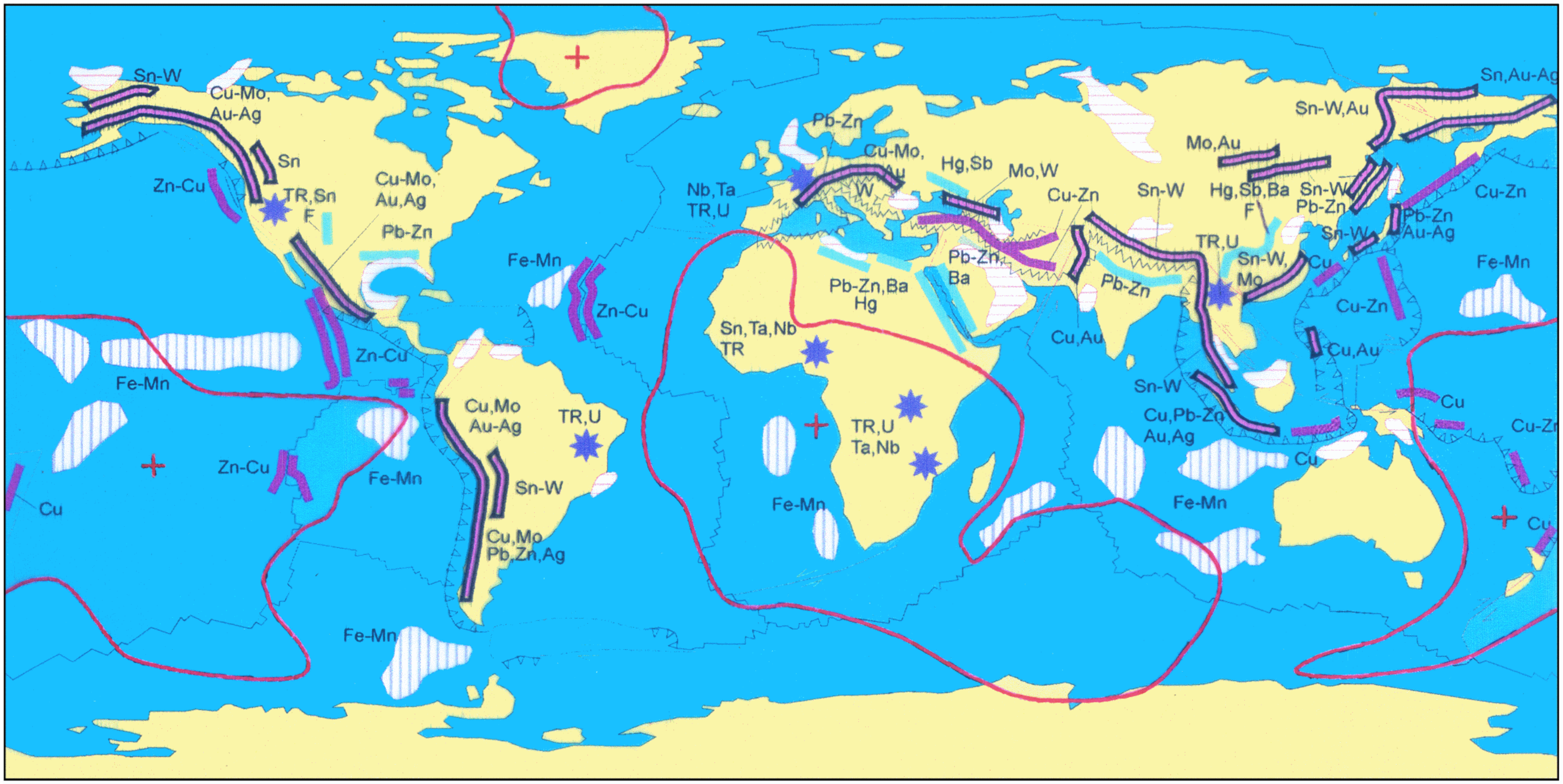

Figure 2. The present-day distribution of the metallogenic provinces of different ages and superplume projections, including the major belts of pyrites deposits (violet), copper–molybdenum and rare-metal deposits (dark-red contoured), telethermal and low-temperature deposits (blue), as well as areas of rare-earth and rare-metal mineralization (blue stars), major oil and gas basins (horizontal hatching), and the fields of ferromanganese concretions in the oceans (vertical hatching). The leading types of mineral deposits are marked by indexes here and in the figures that follow.

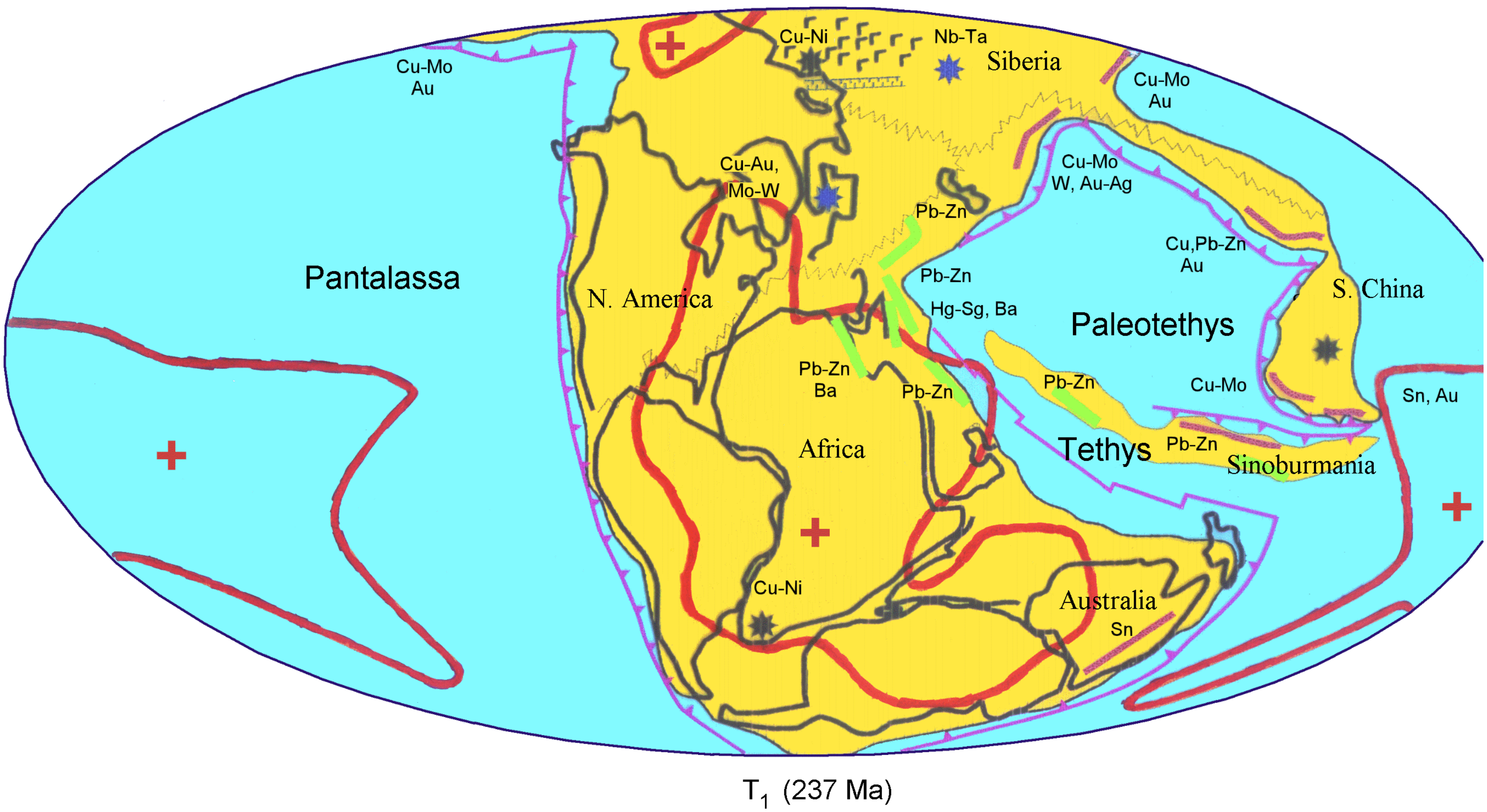

Figure 3. Palinspastic reconstruction for the Early Triassic. This figure and Figures 4 to 9 show superplume projections, trap fields (rrr), spreading axes and subduction zones (violet), collision belts (black fine toothed lines), and belts and areas of rare-metal pyrite and Cu–Mo porphyry (red), telethermal and low-temperature (green), Cu–Ni sulfide (black stars) and rare-earth–rare-metal (blue stars) mineralization of this age.

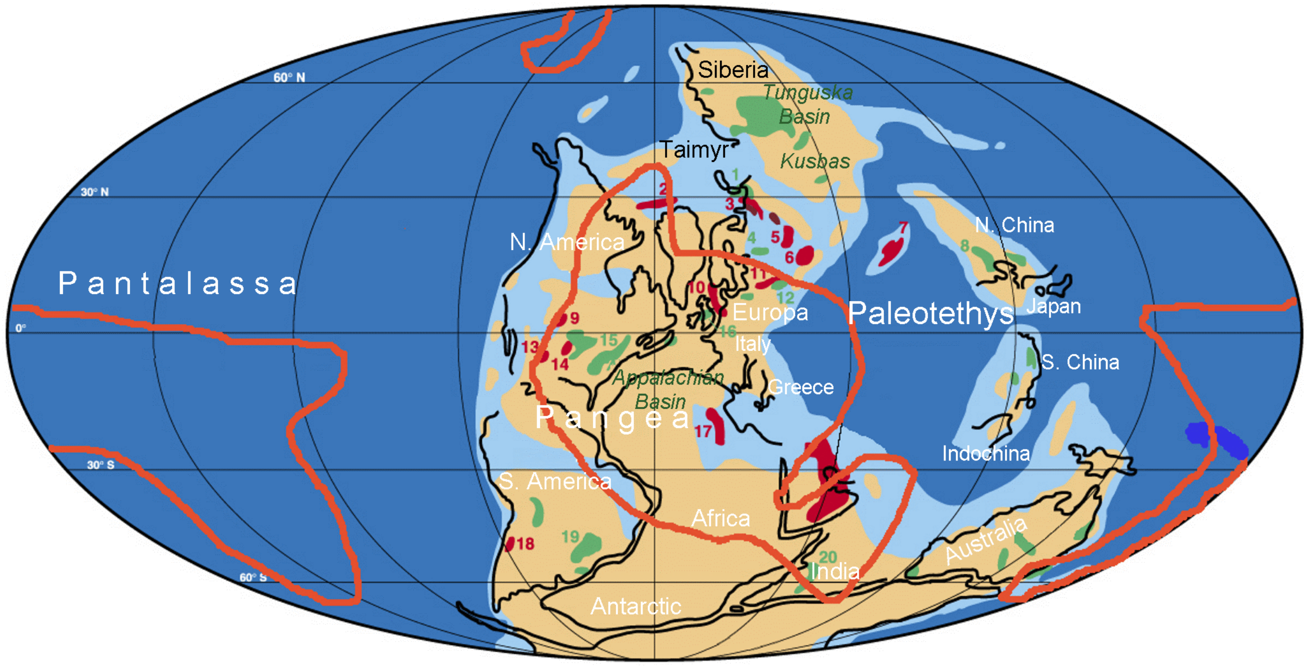

Figure 4. The palinspastic reconstruction for the Late Paleozoic (end of the Carboniferous, 306 Ma). In addition to the plume projections and the oceans, the map shows paleoshelves (blue), the major petroliferous (red) and coal-bearing (green, not considered here) basins of this age. The figures denote the following oil and gas basins: Sverdrup (2), Pechora (3), Volga–Ural (5), Caspian (6), Tarim (7), Rocky Mts. (9), Paleo-North Sea (10), Dnieper–Pripyat (11), Perm (13), Midcontinent (14), Algerian–Libian (17), and Mendoza (18).

heat flow and rising fluids contributed to the formation of not only mineral ore deposits, but also to the accumulation of oil and gas pools, primarily in the sedimentary basins of the passive margins.

In the period of the Late Triassic–Jurassic, Pangea began to break up along the extensive rift systems (Figure 5). The rifting activity was accompanied by trap and alkaline basalt lava flows with the intrusion of dolerite sills in Australia, Antarctica (Ferrar), South Africa (Karroo), West Africa, and North America. The peak of these activities has been dated 183 Ma [*Duncan et al.,* 1997]. These lava flows were most intensive along the lines of the future Africa and Antarctica separation.

Associated with the paleorifts are the provinces of low-temperature barite, fluorite, and telethermal lead–zinc ore deposits in the south of the USA and in North Africa, as well as the oolitic iron ore deposits in West Europe (Lotharingia and Silesia) [*Mitchell and Garson,* 1981]. All of these processes were controlled by the Indian–African superplume. The provinces associated with the active continental margins and island arcs dominated on both sides of the Paleopacific Ocean. Within the projection of the same plume or near it, new oil and gas basins developed in the Gulf of Mexico, West Australia (Carnarvon), and in the Persian Gulf, where hydrocarbon deposits continued to be formed in the passive margin throughout the Mesozoic and Early Cenozoic (Figure 6).

4. Middle Stages of the Wilson Cycle: the Middle of the Mesozoic

During the end of the Jurassic and the beginning of Cretaceous the still continuing breakup of Pangea resulted in the opening of young oceans, primarily of the Indian and Central Atlantic oceans (Figure 7), which is documented reliably by the ages of linear magnetic anomalies in the oceanic crust. New rifts were formed in the other parts of Pangea. The rifting was accompanied by trap and alkaline basalt flows in Brazil (Parana), in Southwest Africa, Northeast India (Rajmahal), and in the North Sea. Associated with the areas of anorogenic granites within the projection of the Indian–African plume are the provinces of Sn–Ta–Nb, rare-earth, and U–Th mineralization in Nigeria (Jos Plateau), Brazil, and Malawi [*Mitchell and Garson,* 1981; *Nechaeva,* 1976]. The Pacific superplume activity seems to have been responsible for the maximum development of thick Early Cretaceous oceanic plateau basalts in the West and Southwest Pacific.

During the same period of time the passive continental margin at the northern edge of the Tethys became active in connection with the beginning of its opening and was characterized by the development of tin and tungsten mineralization (Figure 7). Active continental margins continued to exist with the predominance of gold–silver and rare-metal mineralization, whereas island arcs developed in some areas

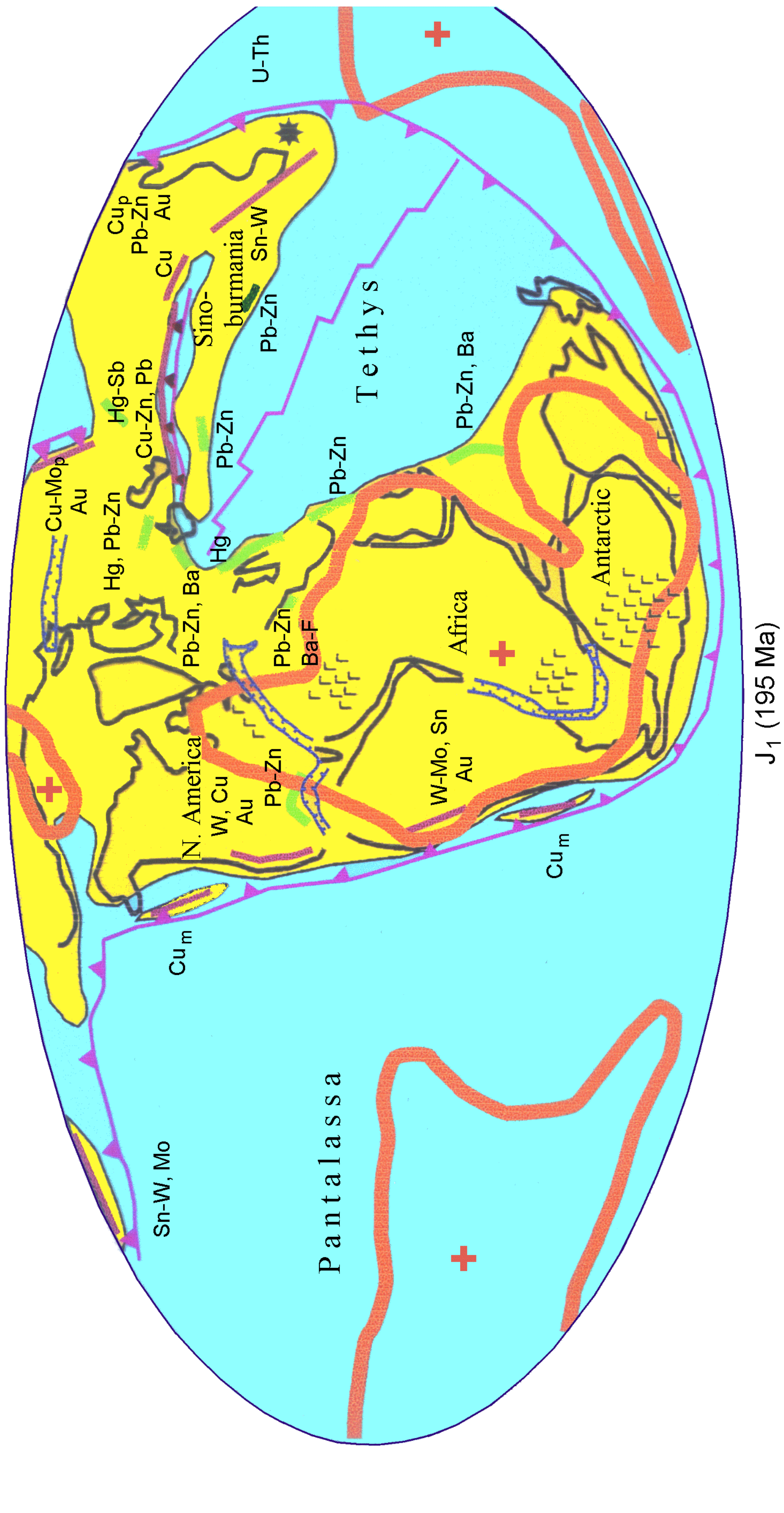

Figure 5. Palinspastic reconstruction for the Early Jurassic. See Figure 3 for the legend.

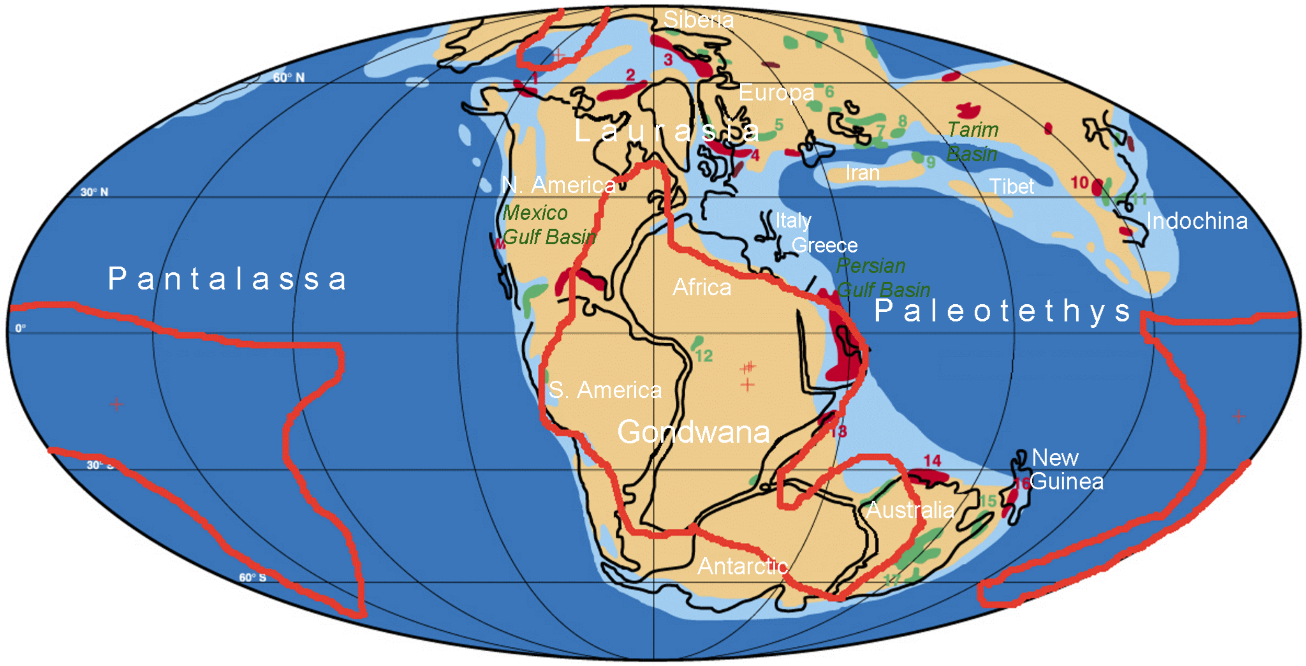

Figure 6. Palinspastic reconstruction for the onset of the Jurassic. Oil and gas basins: 1) Arctic slope of Alaska, 2) Sverdrup, 3) Kara and Barents Seas, 4) North Sea, 10) Sychuang, 13) Indus R. mouth, 14) Carnarvon, 16) Papua. See Figure 4 for the legend.

of its opposite margin during the late Jurassic and in the Cretaceous [*Khain,* 2001], where pyrite ore deposits were formed. This distribution of geodynamic conditions at the active margins of the pacific can be explained by the subduction of the oceanic lithosphere of different ages. Relatively young and hot lithosphere of the Kula Plate subsided under Eurasia, whereas the older and, consequently, heavy and cold oceanic lithosphere of the Farallon Plate was being subducted under the North and South America. The large oil and gas basins of Western and Eastern Siberia, Venezuela, and Columbia also originated in the vicinities of the zones affected by hot plumes (Figure 8).

5. Late Stages of the Wilson Cycle: End of Mesozoic–Cenozoic

The previous trends continued during the end of the Cretaceous and the beginning of the Paleogene (Figure 9). The Central and South Atlantics were combined, and India moved rapidly to the north. The separation of Madagascar from it was accompanied by Deccan basalt flows. Rifting processes developed in the vicinities of the hot plume projections between Australia and Antarctica, and between North America, Greenland, and Europe. Associated with these processes in Greenland was the emplacement of trap basalts and the injection of the basic intrusions of the Skaergaard Complex. In connection with the Tethis closure the dominant environments in South Eurasia were active margins and collision zones with the formation of Cu–Mo, Pb–Zn, and Sn–W ore deposits [*Mitchel and Garson,* 1981].

During the Late Cenozoic rifting processes that took place above the Indian–African Plume during the Late Cenozoic resulted in the separation of the African, Somaly, and Arabian plates (Figure 10). These processes were accompanied by the emplacement of granites with Ta–Nb, rear earth, and U mineralization in East Africa and Arabia. Similar mineralization (for example, the Kaizershtul ore deposit in Germany) is known above small plumes in West and Central Europe. These plumes rise from a low-velocity layer at a depth of some 400 km (Figure 11) and are associated with the massifs of the Variscan basement broken by the late Cenozoic rifts including the Rhine grabens [*Granet et al.,* 1995].

During the Late Cenozoic the geodynamic conditions and mineralization types changed drastically on both sides of the Pacific (Figure 10). In the east the mid-oceanic ridge subsided partially under the continental plate. This caused the predominance of extension in the Basin and Range Province. Tin and rare earth ore deposits are associated with alkaline intrusions there (Mountain Pass and other ore deposits). Some other parts of the American active margin show the development of rare-metal and porphyry copper provinces above the areas of the subsidence of the young and hot lithosphere of the Pacific, Cocos, and Nasca plates. At the same

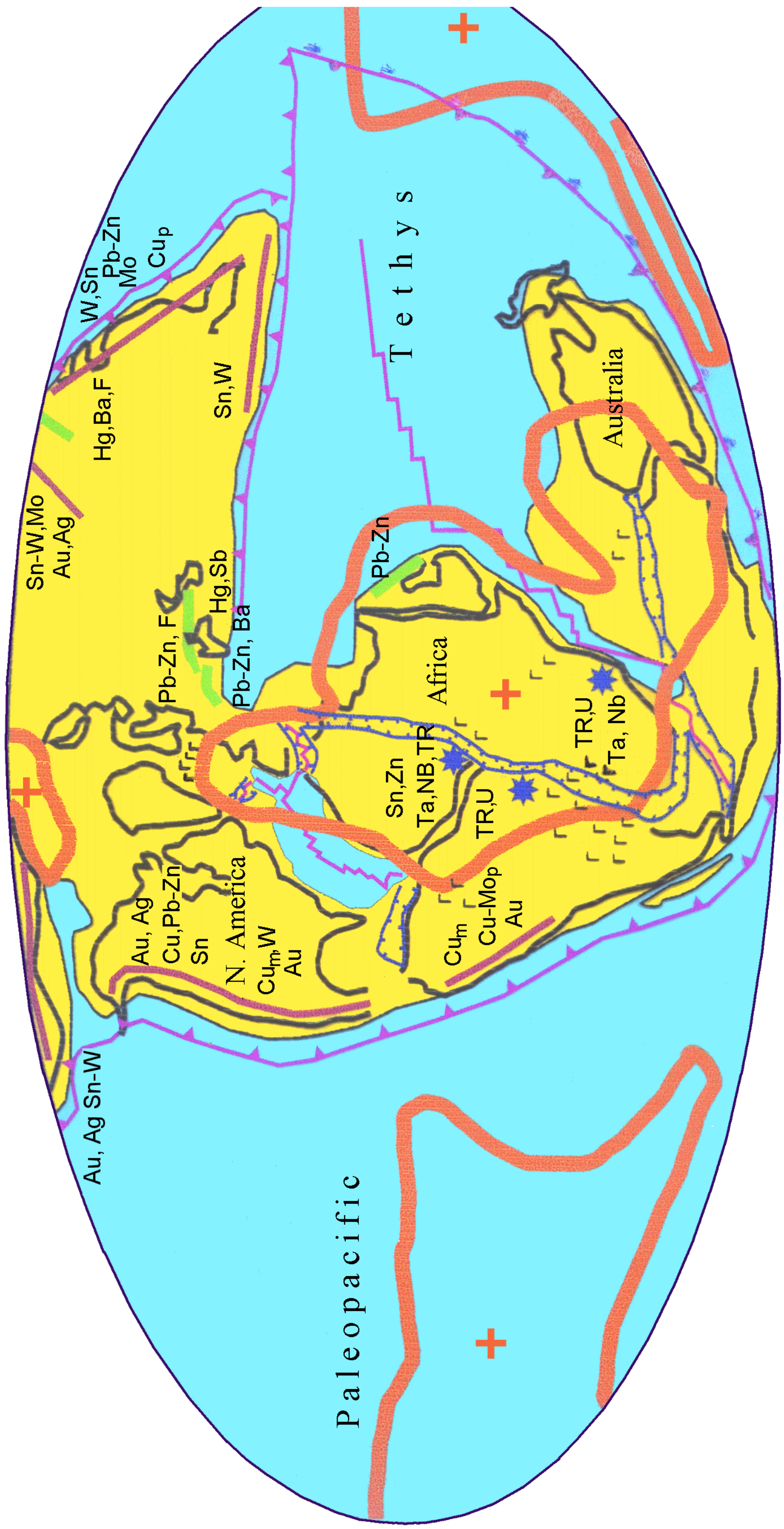

Figure 7. Palinspastic reconstruction for the beginning of the Cretaceous. See Figure 3 for the legend.

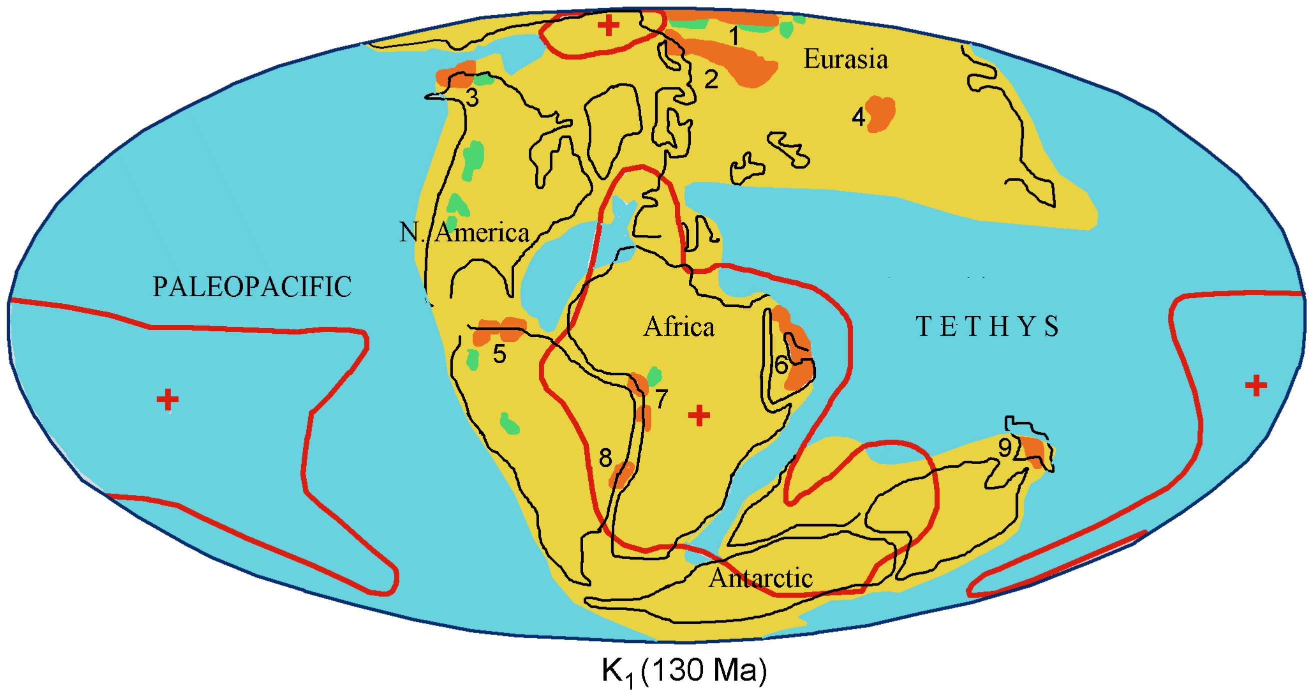

Figure 8. Palinspastic reconstructions for the Early Cretaceous. Oil and gas basins: 1) Lena–Tungusska Basin, 2) West Siberian Basin, 3) a basin at the Arctic slope of Alaska, 4) Tarim Basin, 5) Marakaibo and Barinas Basin, 6) Percian Gulf Basin, 7) a basin in the Gulf of Guinea, 8) Campus, and 9) Papua. See Figure 4 for the legend.

time pyrites deposits dominate in the west in island arcs, where the older and cold lithosphere is subsiding, some of them being replaced along the strikes of the structures by porphyry copper deposits in the segments with the subduction of the hotter and lighter lithosphere [*Gatinskii et al.,* 2000].

Extensive collision belts with mainly rare-metal provinces were formed in South Eurasia in the Alps, Himalayas, and in other regions [*Mitchell and Garson,* 1981]. The continental blocks were gradually combined around Eurasia which, possibly, will become the center of the formation of a new supercontinent, the origin of which will mark the end of the next Wilson Cycle.

6. Discussion of Results

In this paper we attempted to demonstrate that during the latest Paleozoic, Mesozoic, and Cenozoic the formation of the metallogenic provinces had been controlled by changes in the geodynamic conditions and by their positions relative to the projections of major hot plumes. The Wilson Cycle included the formation of Pangea in the environment dominated by the processes of subduction and collision, its disintegration above a deep superplume, dominated by rifting and spreading processes, and the subsequent combination of the continental blocks into a new supercontinent. This scenario seems to valid for the Precambrian and Early Phanerozoic history of the Earth, beginning from the transition of the chaotic multiple convection during the Hadean to the formation of individual continental nuclea at the beginning of the Archeozoic and of the first supercontinent during its end [*Khain,* 1995, 2001; *Kumazawa and Maruyama,* 1994; *Sorokhtin and Ushakov,* 1993]. This cycle was accompanied by a successive change of metallogenic provinces from primarily rare-metal ones via low-temperature hydrothermal, rare-metal and rare-earth, telethermal stratiform, pyrites, and Cu–Mo porphyritic provinces to new rare-metal ones. It appears that the formation of large oil and gas accumulations was restricted mainly to the early and intermediate stages of the cycle.

Two principal mechanisms that controlled the evolution of our planet were responsible mainly for changes in the geodynamic conditions and in the metallogenic provinces in the lithosphere (Figure 12): more shallow plate tectonics, responsible for the combination of continental blocks, and deeper plume tectonics responsible for the break-up of the supercontinents. The former mechanism favored the processes of the accretion of the continental crust and the underlying lithosphere with the respective metallogenic speciation, and the latter was responsible for the predominance of destruction processes and the formation of the provinces of mineral deposits, associated with them [*Gatinskii,* 1985; *Rundkvist et al.,* 1998].

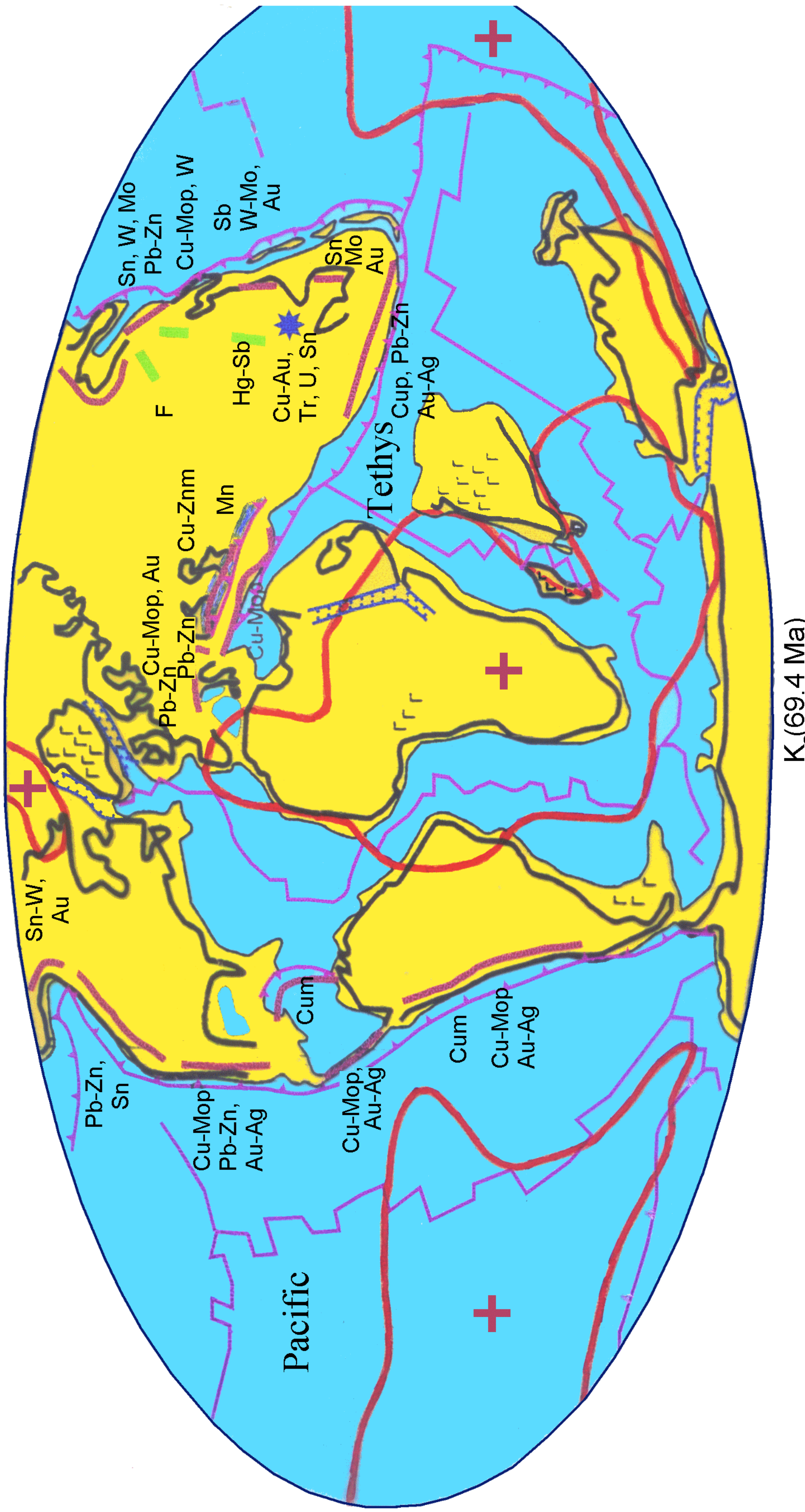

Figure 9. Palinspastic reconstruction for the end of the Cretaceous. See Figure 3 for the legend.

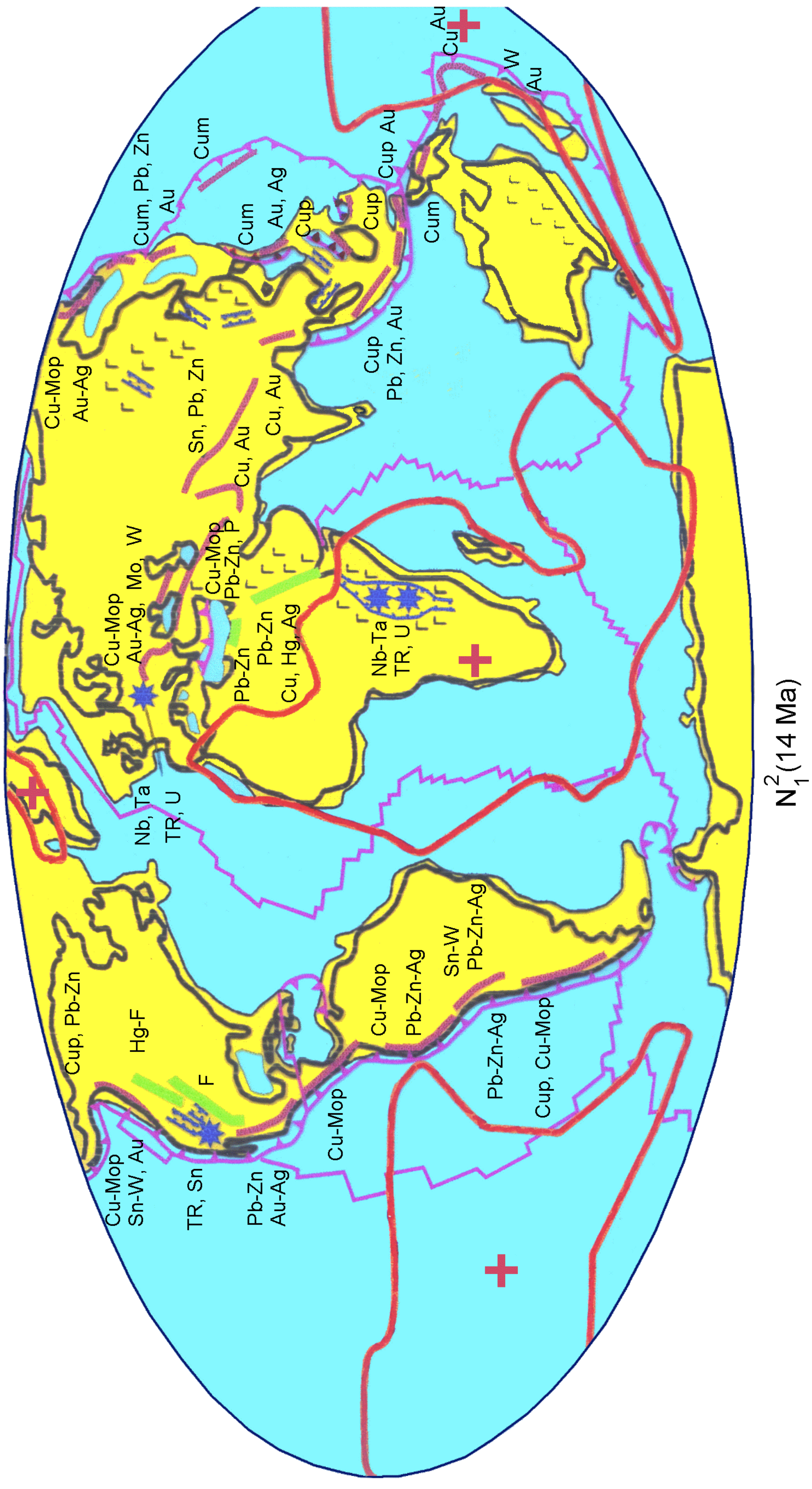

Figure 10. Palinspastic reconstruction for the middle of the Miocene. See Figure 3 for the legend.

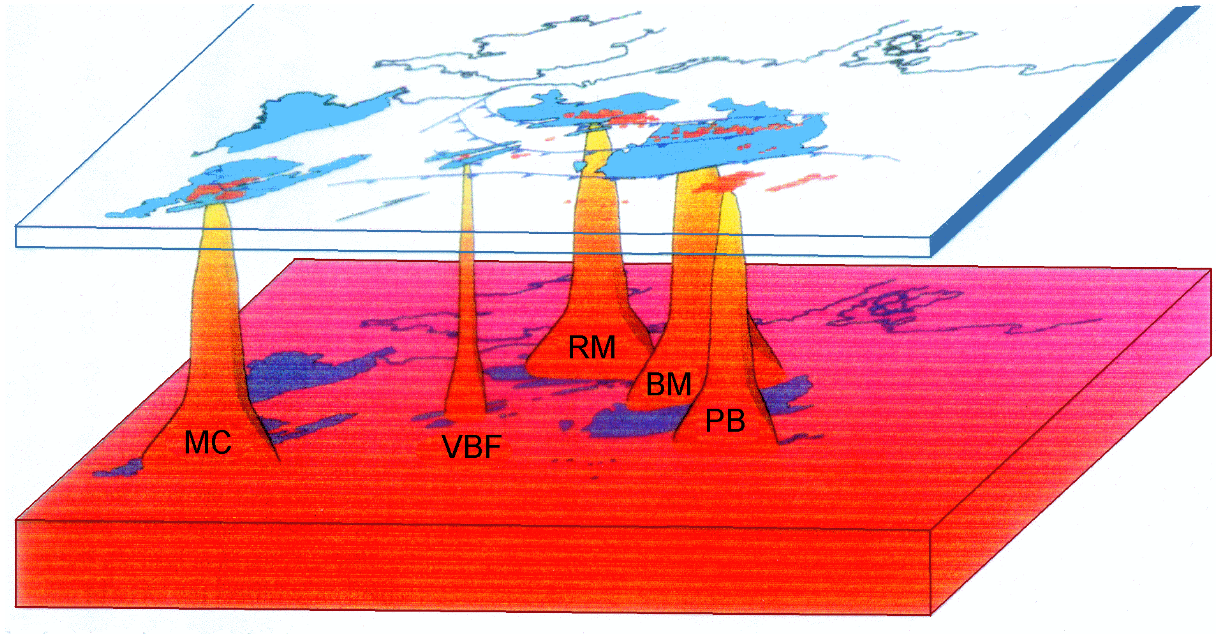

Figure 11. Near-surface plumes rising from depths of about 400 km under the Variscan massifs of West Europe [after *Granet et al.,* 1995]: MC – under the Central France Massif, VBF – under the Vosges mountain range, RM – under the Reno-Hercynian Massif, BM – under the Bohemian Massif, and PB – under the Pannonian Basin. The Cenozoic basalt fields are shown in red among the massifs.

7. Discussion

Two problems are offered here as the subjects of discussion. The first of them concerns the open and closed systems of plume tectonics operation in the upper layers of the lithosphere. The former are known to have developed in highly folded and faulted Precambrian massifs and Phanerozoic fold regions and are usually accompanied by metallic mineralization. Examples can be found in Africa, in Variscan Europe, and elsewhere.

The closed systems originated under large sedimentary basins which precluded the free rise of heat and fluids to the Earth surface, these fluids acting as sources of oil and gas pools (Persian Gulf, Western Siberia, etc.). The second problem concerns the zonal distribution of metallogenic

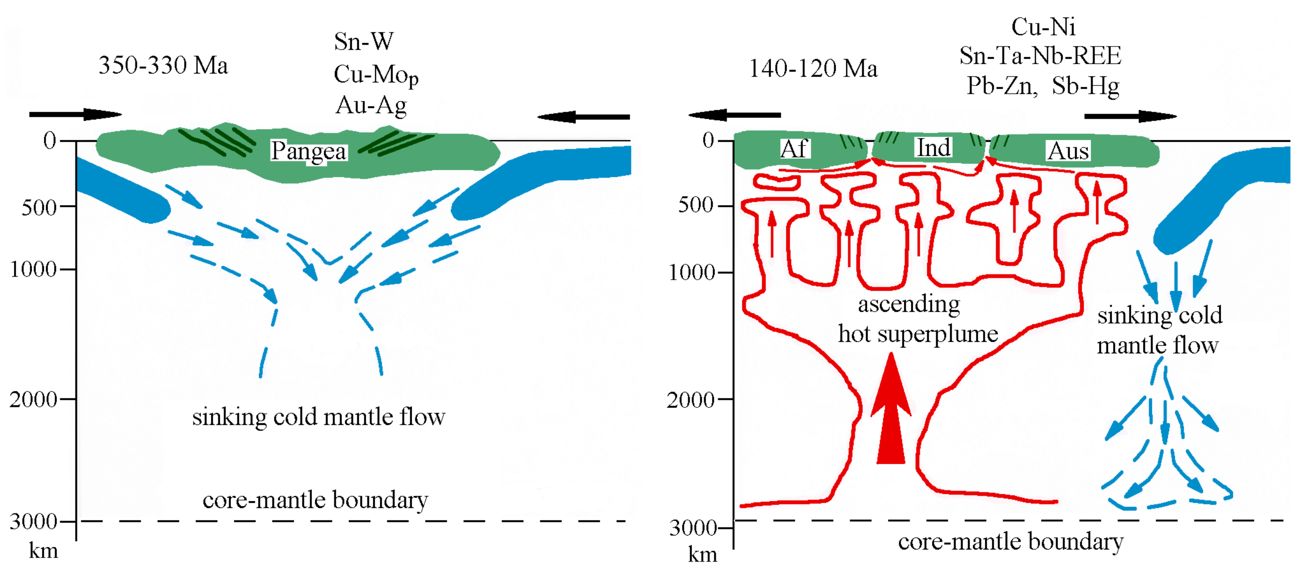

Figure 12. The major mechanisms controlling changes in the geodynamic conditions and metallogenic characteristics of the lithosphere. Af – Africa, Ind – India, Aus – Australia.

provinces above the hot plumes. In many cases, though obviously not always, alkaline-granite and basic-ultrabasic magmatism and associated mineralization are restricted to the apical parts of the plumes, varying in depth, the provinces of telethermal and low-temperature mineralization, to the outer parts of the plumes, and the oil and gas basins, to the peripheral regions of the plume effects. However, these problems are beyond the framework of this paper.

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