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Reviews

The Cretaceous Turn of Geological Evolution: Key Evidence from East Asia

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Abstract: this work focuses on one of the critical points of Earth's history when the Solar System passed through the most distant point of its galactic orbit. During this event, Earth may have suffered from maximum extension, associated with its relative proximity to the Sun at that time, followed by long-term contraction related to its later distancing. This paper is based on generalized data on the Cretaceous evolution of the Earth as a whole and of East Asia in particular. The evidence suggests that major geological processes at this time may be interpreted as transitional changes in the state of Earth. A liquid nature of its core may have reacted to the gravitational and electromagnetic transformations. When the cosmic changes took place at 135-120 Ma, more turbulent flows in the outer core would have favoured the rise of voluminous magmatic plumes and associated fluid flows. These would substantially transform the mantle, crust, hydrosphere, biosphere and atmosphere. In particular, plume-related melting of overlying subducting slabs and lower continental crust could have initiated numerous adakitic melts that formed the East Asian Adakitic Province. These and associated juvenile events produced numerous metallic ore, coal, gas and oil deposits. The Cretaceous is one of the most significant resource-producing periods.

Key words: Cretaceous, geological evolution, galactic orbit, super plume, adakitic rocks, coal, ore and petroleum resources

1 Introduction

Over a decade ago, the Bulletin of the Far Eastern Branchof the Russian Academy of Sciences published a paper entitled "On the galactic influence on Earth during the last seven hundred million years" (Nechaev, 2004). This paper presented a hypothesis, which is used as a basis for this work. It was written in Russian, and because of this, an outline of this hypothesis is first needed here as an introduction.

The galactic seasons of the Earth indicate significant changes caused by its distance from the Sun while that star was flying along its elliptical orbit (Weissman, 2014). Under the gravitational influence of a huge mass at the galactic center, the Solar System, including Earth, became extended when it moved closer to the center and then contracted back towards the Sun when it became more distant. So the galactic winters on the Earth coincided with the 'summer' (closer to the galactic center) position of the Solar System and vice versa. Galactic winters occurred

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during the Vendian, Carboniferous-Permian and Late Cenozoic periods, times characterized by long-term decreases in global temperature and biodiversity, in addition to the formation of the supercontinents (Carr and Bell, 2014; Scotese, 2002; Sepkoski,1984). In the warmer seasons, the Earth resembled Venus (Smrekar et al., 2014) with its widespread mafic volcanism, disseminated thicker crust, dense ‘gas-laden’ atmosphere and associated strong greenhouse effect (Berner and Kothavala, 2001; Ronov, 1993; Scotese, 2002).

As slower orbital velocities of the Solar System operated in the past, the galactic year of the Earth was about 500 million years in the late Precambrian (the time interval between the formations of the Rodinia and Pannotia/Gondwana supercontinents), 350-400 million years from the latest Precambrian to the Permian (the Pannotia/Gondwana-Pangea cycle), and 250-300 million years after the Permian (Fig. 1).

Many other ideas exist regarding Earth’s evolution. For example, Kotelkin and Lobkovsky (2007), Lobkovsky et al. (2004) and Nance et al. (2014) all consider the major solid earth changes, such as the supercontinent cycles and related biogeochemical processes, as being solely controlled by the mantle and core dynamics, including subduction of large volumes of oceanic lithosphere, avalanching them to the core-mantle boundary, and the subsequent formation of super plumes (Larson, 1991). However, these researchers concentrated on our planet per se, as though it behaves as an independent body within the Universe. The presented models, however, can adapt a galactic influence on geological evolution (Lobkovsky et al., 2004).

Other authors focused on the Sun, Earth, and galactic relationships. Shaviv and Veizer (2003) found a correlation between changes in Earth’s climate, solar radiation and wind intensity, and the galactic ray flux. According to this model, the Earth became colder and suffered from severe geological crises when passing the spiral arms that generate intensive cosmic rays. Following and developing this hypothesis, Wendler (2004) suggested that significant turbulent magnetic influences of the spiral arms resulted in reversing geomagnetic fields, while the geomagnetic regime with sparse reversals (superchrons) occurred while the Solar System was positioned in the space between the spiral arms. However, this seems to conflict with a more recent study showing that enhanced turbulence in Earth’s liquid core produced the geomagnetic regime with sparse reversals, one of which took place during the warm Cretaceous time (Kurazhkovskii et al., 2015).

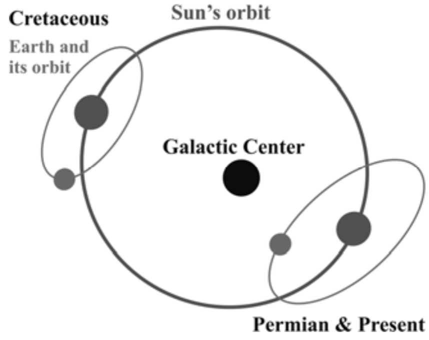

Fig. 1. A scheme illustrating the suggested temporary positions of the Sun and Earth relative to the galactic center (after Nechaev, 2004)

Barenbaum (2012, 2013 and references therein) found even more associations of geological events with “the impact of the Galaxy at the moments when the Solar System gets into the jet flows and spiral galactic arms” (Barenbaum, 2012; page 1). The geological events were considered to be mostly geological crises, although some gradual, evolutionary changes such as the carbon cycle and the history of phosphate and petroleum accumulation were included. As with the previous authors, Barenbaum concluded that passage of the Solar System through the Milky Way’s spiral arms or other gas and dust clusters and the free space between them controlled Earth’s evolution.

Such an interpretation, however, seems to be incomplete, because catastrophic events by their very nature indicate the sporadic rather than normal time succession of the galactic year. In addition, previous researchers ignored the galactic center, whose influence must be highly significant. Earth is circling round it along with the entire Solar System. Where can more solid evidence of its significance be sought? Regardless of this, a correlation between the superplumes, superchrons, supercontinent cycle, warm climates, and related long-term geological processes has been defined for at least Phanerozoic time, although the (external or internal) causes are still under discussion.

2 Approaches and Data Sources

This work is devoted to general tendencies of geological evolution and concentrates on one of its critical points, the Cretaceous Period. It considers data that have already been compiled, generalized and interpreted to a certain degree. Because of this, and to avoid breaking the logic within the reasoning, the results and discussion are combined in the text below.

The first author’s approach for studying the galactic influence on Earth, focusing on long-term and gradual (evolutionary, seasonal) changes, principally differs from other approaches in that they pay more attention to sharp (critical or catastrophic) events such as mass extinctions and comet impacts (for example, Shaviv and Veizer, 2003; Wendler, 2004; Barenbaum, 2012, 2013; and references therein).

3 Results and Discussion

3.1 Phanerozoic and Late Proterozoic

According to Nechaev (2004), the Solar System periodically passes through critical points of its galactic orbit (apo- and perycenters) that should lead to some global phases of geological evolution. The last event of this kind happened in the Cretaceous when our star (the Sun) likely passed the apocenter, the most distant point of its galactic orbit. During this event, the Earth could be expected to undergo maximum extension, associated with its relative closeness to the Sun at that time and then long-term contraction related to its distancing. Fig. 2 shows other associated processes, including increase in surface temperature (Scotese, 2002), atmospheric carbon dioxide (Berner and Kothavala, 2001), and sea levels (Hallam, 1992; Snedden and Liu, 2010), as well as the intensive development of modern fauna (Sepkoski, 1984), volcanic activity (Ronov, 1993), ophiolite production (Dilek, 2003), deep-mantle sourced igneous rocks such as kimberlites (Jelsma et al., 2009) and carbonatites (Berger et al., 2009), and petroleum source rocks (Klemme and Ulmishek, 1991). This period also involved the break-up of the Pangea super continent (Scotese, 2002) and crustal growth, based, in particular, on a compilation of global zircon Hf-isotope data and dating (Nance et al., 2014; Roberts and Spencer, 2014; Roberts, 2012; Stern and Scholl, 2010). The cited zircon dating confirms the idea (Nechaev, 2004) that the galactic year of the Solar System, controlling the super continent cycles, was longer in the past. Indeed, the most significant zircon peaks in the U–Pb histogram, which indicate super continent assembly, occurred at 2700, 1850, 1100, 1000, 500, and 250 Ma (Roberts, 2012; page 998).

The Cretaceous evolutionary turn was reflected by a specific geomagnetic field (Granot et al., 2012; Molostovskii et al., 2007; Wendler, 2004), including a long period when reversals were sparse or too frequent for detection (Jalal Hyperchron, N88, 127-83 Ma). This period was also characterized by maxima of chaotic magnetic disturbances, suggesting enhanced turbulence in Earth's liquid core (Kurazhkovskii et al., 2015). Earth's dynamo-machine may not have fully functioned at this time (Molostovskii et al., 2007). Similar magnetic features characterized our planet during the Kiama Hyperchron (R81, 313-267 Ma) and Khadar Hyperchron (R98, 484-462 Ma), corresponding to the evolutionary turns that occurred during the Carboniferous-Permian galactic winter at the perycenter (perygalacticon) and the Ordovician galactic summer at the apocenter (apogalacticon) (see Fig. 2; Molostovskii et al., 2007; Wendler, 2004; and references therein).

The following includes a compilation of the data and their interpretation on the Cretaceous evolution of Earth as a whole, and in southern Far East Russia in particular, where the authors are most familiar with the geology.

3.2 Cretaceous Turn of Geological Evolution

3.2.1 The World

Fig. 3 shows some geological evidence of this turn. The global plate reorganization (Matthews et al., 2012; Vaughan, 1995), which is indicated by a rose-purple bar to the right of the time scale in Fig. 3, occurred 125-100 Ma with a maximum at 100-105 Ma. It was most likely related to the giant 'super plume' initiated at the core/mantle boundary (Larson, 1991). Primarily, Larson suggested that it arose under the Pacific Ocean floor at 125 Ma from an unclear cause, while Utsonomiya et al. (2007) placed its genesis within massive lithospheric subduction near the centre of Rodinia. In light of our 'galactic' interpretation, it may be considered as the most important of igneous events related to the suggested intersection of the galactic orbit apocenter. Impulses of mafic magmatism in Gondwana, forming the Parana-Etendeka and Comei-Bunbury large igneous provinces at 134-132 Ma (Martinez et al., 2014; Peate, 1997; Zhu et al., 2009), were probably first, but later ones included extensive oceanic plateaus, such as the now dispersed 120 to 90 Ma Ontong Java-Manahiki-Hikurangi submarine remnants (Taylor, 2006). This extreme voluminous magmatic activity was accompanied by the influx of hundreds of gigatons of carbon into the atmosphere. This event is indicated by the early Aptian (ca. 117 Ma) carbon isotope records of marine carbonate, marine organic carbon, and terrestrially photosynthesized carbon by a 3‰–5‰ negative excursion (Jahren, 2002). This and similar influxes probably initiated the oceanic anoxic events (Hu et al., 2012 and references therein; Martinez et al., 2014) and it resulted in the incorporation of huge amounts of carbon and hydrocarbons through the biogenic cycles in the hydro- and atmospheres. The voluminous extreme release of magma and fluids from Earth's interior reached their apotheosis at 125-100 Ma. They were most likely caused by some deformation in the Earth's outer core that enhanced its turbulence (Kurazhkovskii et al., 2015), and partial closure of the deep channels under elevating influence of the Earth's gravitation. Our planet released 'escaped vapor' at the beginning of its seasonal contraction. Formation of the colossal petroleum reserves sourced by the Aptian-Turonian strata (about 1/3 of all the

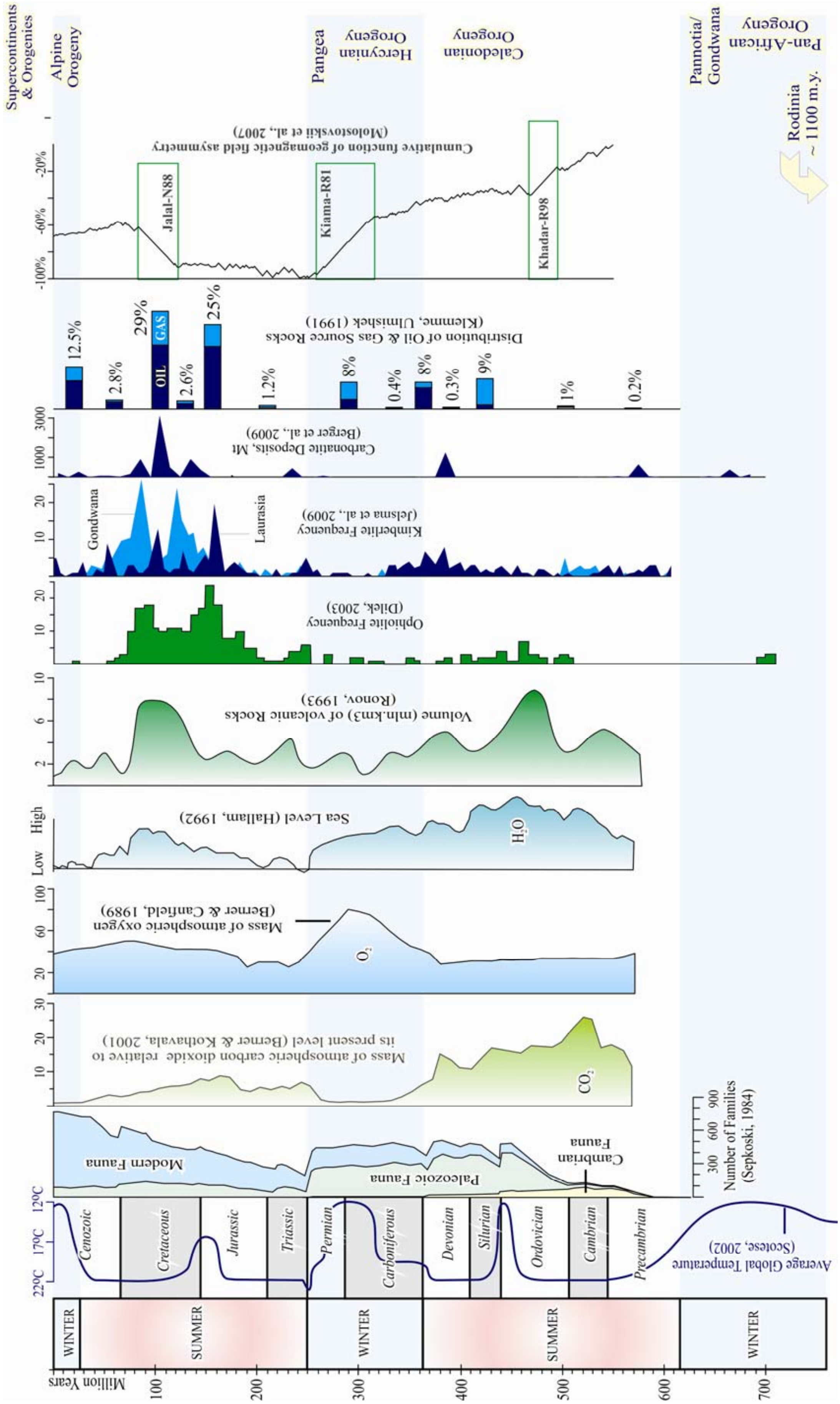

Fig. 2. The proposed galactic seasons and related global geological changes.
After Nechaev (2004) with additions from Berger et al. (2009), Dilek (2003), Jelsma et al. (2009), Molostovskii et al. (2007) and Ronov (1993). Green rectangles indicate the relatively long periods of stable-polarity geomagnetic field.

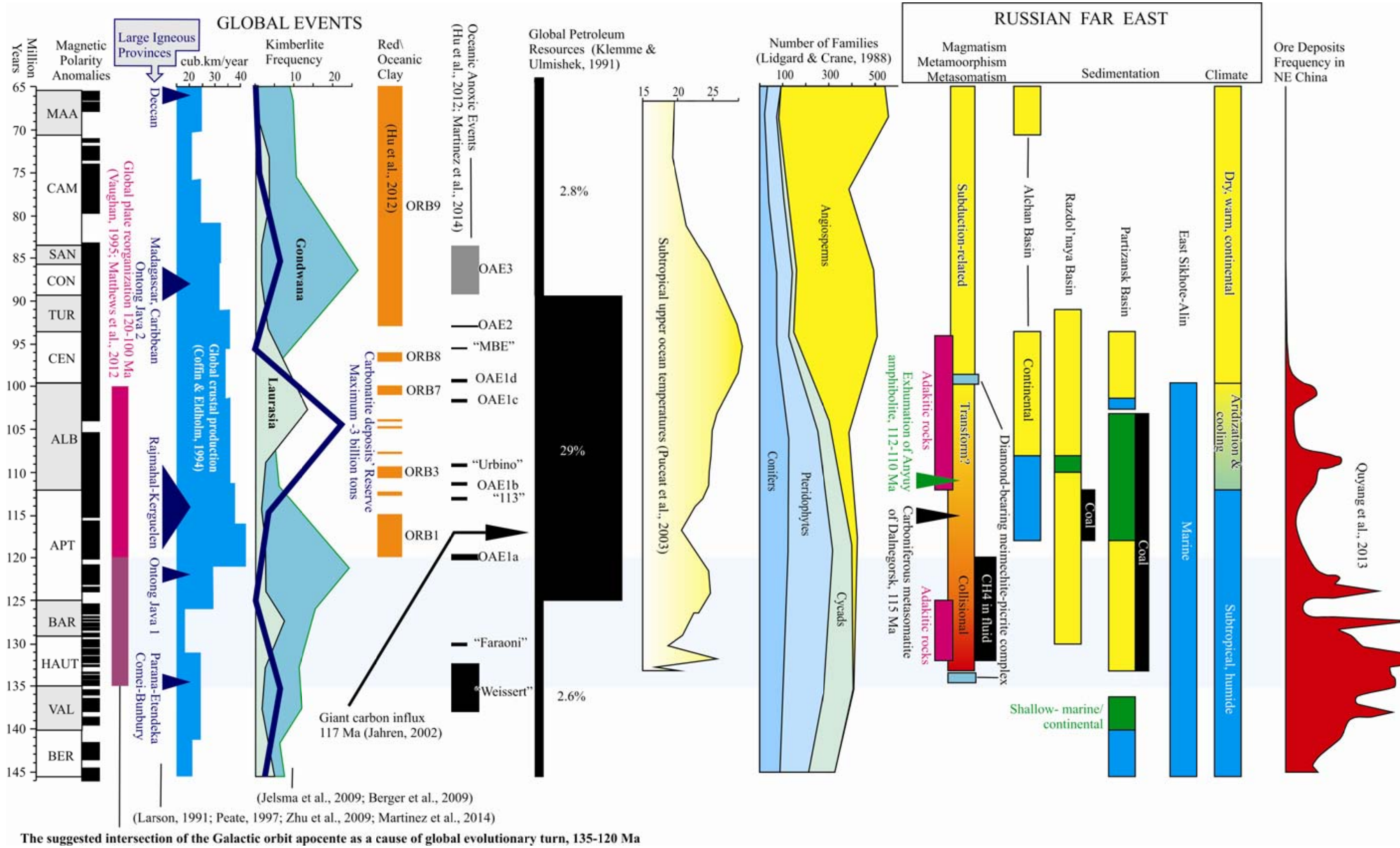

Fig. 3. Global and Far Eastern Russia geological changes related to the suggested passage of the galactic orbit apocenter as a cause of the global evolutionary turn during the Cretaceous.
The Far Eastern Russia changes are presented after Baskina et al., 2006; Berdnikov and Karsakov, 1999; Chashchin et al., 2014; Faure et al., 1994; Geological …, 2014; Golozoubov et al., 2006; Jahn et al., 2015; Krasilov, 1967; Kruk et al., 2014; Markevich et al., 2000; Markevich, 1995; Oleynikov et al., 1990; Podolyan et al., 1997; Prikhod'ko et al., 2009; Sakhno et al., 2011; Sharudo, 1972; Simanenko et al., 2006; Volynets, 2009; Wu et al., 2017.

world's oil and gas reserves) was one of the great economic results of this escape (Klemme and Ulmishek, 1991; Larson, 1991).

Biogenic sedimentation, which predominated in the Early Mesozoic oceans, started being replaced by terrigenous deposits at about 120 Ma, when oceanic red clays appeared (Hu et al., 2012; and references therein). This process may be associated with the uplift of mountains on the continents that were also linked to the start of Earth's contraction and associated plate reorganization.

The climate reacted to the change of galactic environment indirectly. The direct reflection of the Sun's distancing would cause gradual cooling and aridization on the Earth's surface. However, the temperature was gradually increasing throughout the Early Cretaceous, reaching a maximum in the late Albian-early Turonian (Hu et al., 2012; Huber et al., 2002; Puceat et al., 2002), when the influxes of greenhouse gases associated with volcanic activity were most intensive. After the Turonian, steady cooling occurred until the end of the Cretaceous, so that climate reflected the galactic event with a significant time delay (20 Ma or more).

Biogenic changes indicate the Cretaceous turn of geologic evolution in different ways. For example, large dinosaurs that may be considered as a symbol of the Mesozoic became extinct at the K/T boundary, while angiosperms (flower plants) symbolizing the modern flora (Lidgard and Crane, 1988) first appeared just at the suggested Sun's passage through the galactic apocenter.

3.2.2 Southern Far East Russia and adjacent regions

Major tectonic reorganizations, changes of magmatism, sedimentation and significant metamorphic events occurred in this area in the Early-Middle Cretaceous, as elsewhere in the world (Fig. 3). The regional climate, however, did not change in the Cenomanian-Turonian as in many other regions of the world, but changed in the Albian (Krasilov, 1967; Markevich, 1995), closer to the suggested galactic event. This difference might be related to the considerable distance between Far Eastern Asia and the main volcanic provinces positioned in the intraoceanic regions.

The major orogenic phase, that finally consolidated the Sikhote-Alin terranes, happened during the late Aptian – early Albian (115-110 Ma). This event is reflected in isotopic dating of mica from the Anyuy metamorphic dome (Faure et al., 1995; Kruk et al., 2014) and hydrocarbon metasomatic rocks from the Dal'negorsk ore district (Baskina et al., 2006), that are close to the mid-Cretaceous plate reorganization in both the Pacific and more globally (Matthews et al., 2012; Vaughan, 1995).

The magmatic activity (K-Ar age = 134.4 ±1.0 Ma; Prikhod'ko et al., 2009) started with volcanic eruptions of the diamond-bearing meymechite-picrite complex (Ivanov et al., 2005; Oktyabr'skii et al., 2010; Prikhod'ko and Petukhova, 2011; Shcheka et al., 2006) that continued from the Jurassic and was followed by mid-Cretaceous plume-related intrusive activity (U-Pb zircon ages = 149-161 and 96-98 Ma; samples 26, 28, and 32; http://test-wms.vsegei.ru/geochron_atlas/, in Russian). This was accompanied by S-type collisional granites (Valanginian-Hauterivian) containing methane-rich fluid inclusions (Berdnikov and Karsakov, 1999) and then transitional S- and I-type granites of unclear (transformed?) geodynamic nature (Kruk et al., 2014). This unusual magmatic suite was replaced by Upper Cretaceous subduction-related volcanics forming the East Sikhote-Alin Belt and the Alchan zone and associated granitic intrusions (geological processes in the lithospheric plates subduction, collision, and slide environments, 2014; Jahn et al., 2015).

Recently, some adakitic rocks have been identified to the west of the East Sikhote-Alin volcanic belt (Chashchin et al., 2014; Sakhno et al., 2011; Wu et al., 2017). These rocks occurred at the northeastern edge of a huge magmatic province occupying almost all of the East Asian territory (Fig. 4). This province, which is comparable with known Large Igneous Provinces in terms of at least size and shape, started forming at 190 Ma and terminated at 80 Ma with its culmination in the early Cretaceous (Davis, 2003; Wu et al., 2005). Its origin is obscure: nothing similar is known in the modern world, where adakitic complexes have a localized distribution in areas of intensive interaction between oceanic slabs, mantle wedges and continental crust associated with anomalous subduction and/or post-collisional continental environments (Castillo, 2012). It should be noted that similar tonalite–trondhjemite–granodiorite and sanukitoid suites were relatively common in the Archean, before later styles of subduction were developed (Martin et al., 2005) or occurred in an unusual short-term form (Moyen and van Hunen, 2012).

Several geodynamic models have been proposed to explain the phenomenon of the Early Cretaceous adakitic rocks of East Asia. Most of these suggest partial melting of either lower mafic continental crust that was thickened, underplated and delaminated or subducted slab with windows and mantle diapirs ascending through them (Davis, 2003; Ishihara and Chappell, 2008; Ji et al., 2007; Kiji et al., 2000; Liu et al., 2012; Sui et al., 2007; Takahashi et al., 2005; Tsuchiya et al., 2007; Wang et al., 2006a, 2006b, 2007; Wee and Park, 2009; Wee et al., 2007; Wu et al., 2005; Xu et al., 2012; Yang and Zhang, 2012; Zhang et al., 2004, 2006, 2010). All of the models

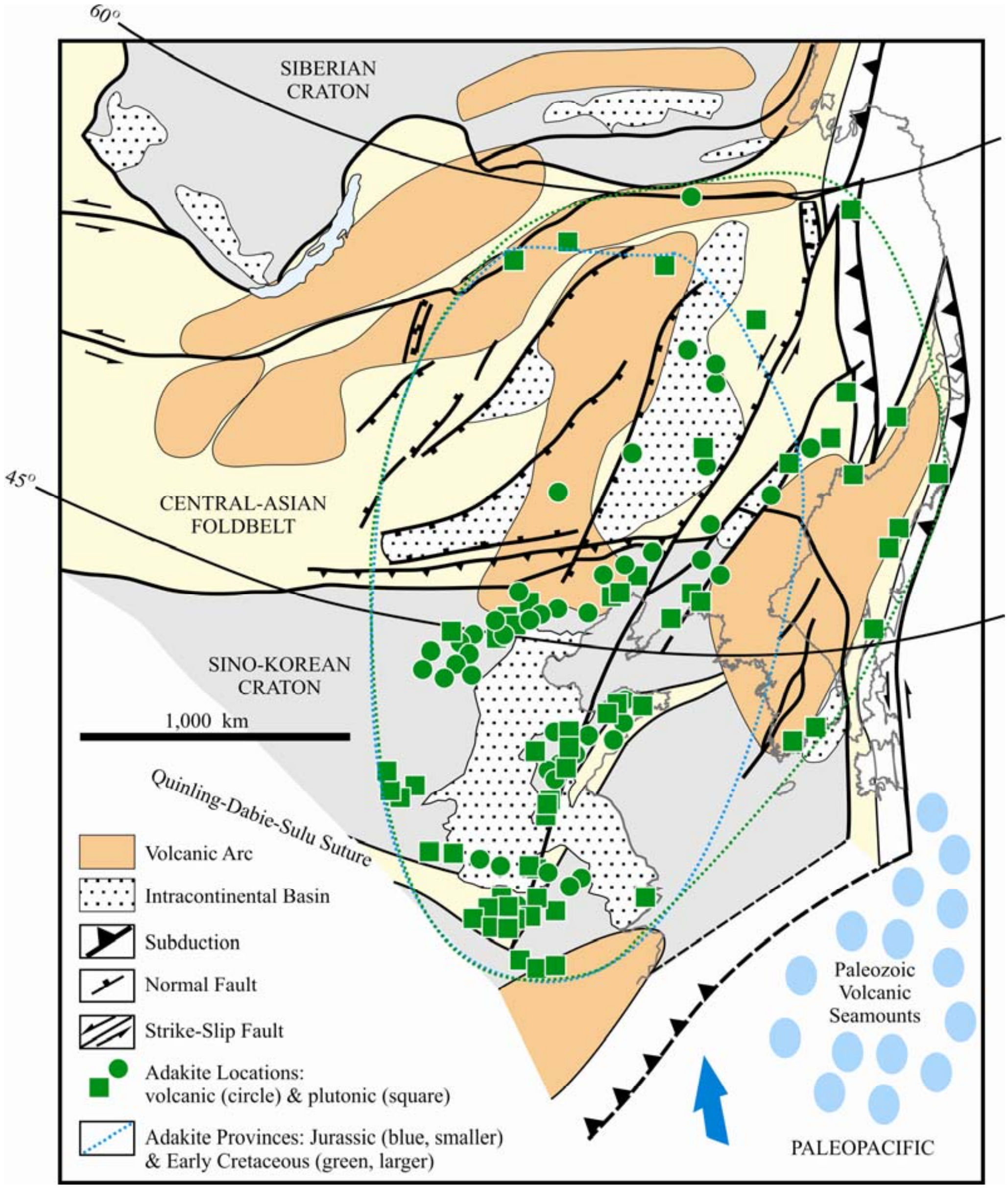

Fig. 4. Late Jurassic-Early Cretaceous paleoreconstruction of East Asia.
After Parfenov et al. (2010) with some additions from Isozaki et al. (2010) and Maruyama et al. (1997)) showing the Mesozoic (80-190 Ma) adakitic rock locations (Berzina et al., 2012; Davis 2003; Gonevchuk et al., 1999; Ishihara and Chappell 2008; Ji et al., 2007; Kiji et al., 2000; Liu et al., 2012; Sakhno et al., 2011; Sorokin et al., 2012; Sui et al., 2007; Takahashi et al., 2005; Tsuchiya et al., 2007; Wang et al., 2006a, 2000b, 2007; Wee and Park, 2009; Wee et al., 2007; Wu et al., 2005; Wu et al., 2016; Xu et al., 2012; Yang and Zhang, 2012; Zhang et al., 2004, 2006, 2010).

are based on a limited knowledge of the Jurassic-Lower Cretaceous adakitic rocks in the region. Recent data (Wu et al., 2017) and its compilation (Fig. 4) shows that this province extends over very different geological terrains, namely the Sino-Korean Craton and Dabie-Sulu Collisional Belt, as well as the Sikhote-Alin, Khanka, Bureya, Jiamusi and other blocks of the eastern Central-Asian Fold Belt that are characterized by continental crust of highly variable thickness, structure and composition (Parfenov et al., 2010). It is difficult to imagine that continental crust was thickened enough throughout this geologically heterogeneous territory to provide such widely-distributed adakitic melts. Moreover, many adakitic rocks of the province have isotopic and geochemical affinities related to subduction of the oceanic lithosphere and/or associated basaltic underplating of continental lithosphere (Chen et al., 2013; Wu et al., 2017). Alternatively, a super plume could provide a heat source for submelting of such a voluminous geological body. Notably, the previously-mentioned meimechite-picrite complex may be considered as direct evidence of such plume-related activity. Further evidence that is suggestive of a plume/rift presence are the numerous sedimentary basins distributed throughout East Asia in the Cretaceous (Okada, 1999). The following model is suggested here in order to explain the East Asian Large 'Adakitic' Province (Fig. 5).

A super plume rising from the boundary between the mantle and outer core (Larson, 1991), arrived below an oceanic slab, flattening its subduction profile under a voluminous region (thousands of kilometers across) of the East Asian continental margin for tens of millions of years in the Jurassic and especially during the early-middle Cretaceous. Numerous slab windows, developed via lateral extension above the plume, could provide heat flows ascending through the slab, thus generating magmatic intrusions and fluid flows. A combination of partial melts in the upper slab, a thinned mantle wedge and lower crust, produced a complex suite of arc-type adakites, normal subduction-related rocks (volcanics and granites) and continental-type adakites accordingly. Some plume-related rocks, like those belonging to the meymechite-picrite complex of Sikhote-Alin (Prikhod'ko and Petukhova, 2011; Prikhod'ko et al., 2009; Shcheka et al., 2006) also formed a part of this suite.

This model does not conflict with other processes that connect adakites with melts derived from downgoing oceanic slabs, or over thickened continental crust, or underplated and delaminated crust. It merely presents a general scenario that may include all of these mechanisms. Such a scenario is not common in present-day tectonic settings, although a localised interaction of plume and subduction, though less flat in style, has recently been discovered with the help of seismic tomography in the northern Tonga Arc (Chang et al., 2016). These Tongan arc adakites take part in the assemblage of subduction-related rocks (Faloon et al., 2008). The above examples

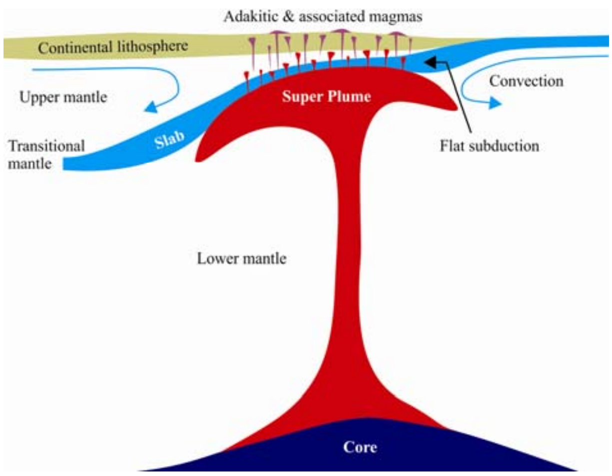

Fig. 5. Cartoon illustrating the super plume-subduction relationship producing the East Asian Large Adakitic Province.

most likely indicate that a specific interrelationship between super plumes, subducted slabs, mantle wedges and continental crust was involved in the Cretaceous phase of geological evolution, caused by turbulence in Earth's liquid core. Abundant slab avalanches could also be associated with these processes (Nance et al., 2014).

Sedimentation differed in the northeastern and southwestern parts of the Far Eastern Russian region. Coal-bearing sediments comprise parts of the Alchan, Razdol'naya, and Partizansk basins in the southern and western areas. A major evolutionary change in the Albian began when continental deposits replaced shallow-marine sediments in this region (Golozoubov et al., 2006; Krasilov, 1967; Markevich et al., 2000; Markevich, 1995; Oleynikov et al., 1990; Podolyan et al., 1997; Sharudo, 1972; Simanenko et al., 2006; Volynets, 2009). In the east and north, thick units of terrigenous marine sediments accumulated in the Early Cretaceous. They formed in a deep-sea basin partly (in the south and southeast) separated from the ocean by a volcanic arc (Khanchuk et al., 2016; Nechaev et al., 1999). This basin was closed in the mid-Cretaceous, while its sedimentary units were accreted onto the continent. After this, the newly-formed fold belt was covered by subduction-related volcanics.

The Early and middle Cretaceous fluid flows from Earth's mantle were likely agents for the formation of numerous hydrothermal mineral deposits. In Far East Russia, they include base-, precious-, and rare-metal ores associated with granites and adakitic rocks (see Fig. 3 showing ore deposit frequency in NE China after Ouyang et al., 2013). In addition, large coal and petroleum resources appeared (Nechaev et al., 2015; Podolyan et al., 1997). Fig. 6 presents the scheme of the fold-and-thrust structures associated with the oil and gas occurrences in Primorye. These structures were formed largely during the Cretaceous phase of geological evolution.

4 Conclusions

Data is presented here as evidence that the Cretaceous time in Far East Russia and throughout the world was characterized by diverse magmatic, tectonic and sedimentary processes and events, many of which seem atypical of many 'normal' plate-tectonic settings. Because of this, the Far Eastern Russian region in the Early Cretaceous is commonly interpreted as a transform plate boundary whose characteristics are not distinct (Khanchuk et al., 1996, 2016; Geological processes in lithospheric plate subduction, collision, and slide environments, 2014; and others). The presented 'galactic' interpretation of geological evolution can provide fresh insights into this period of Earth's history.

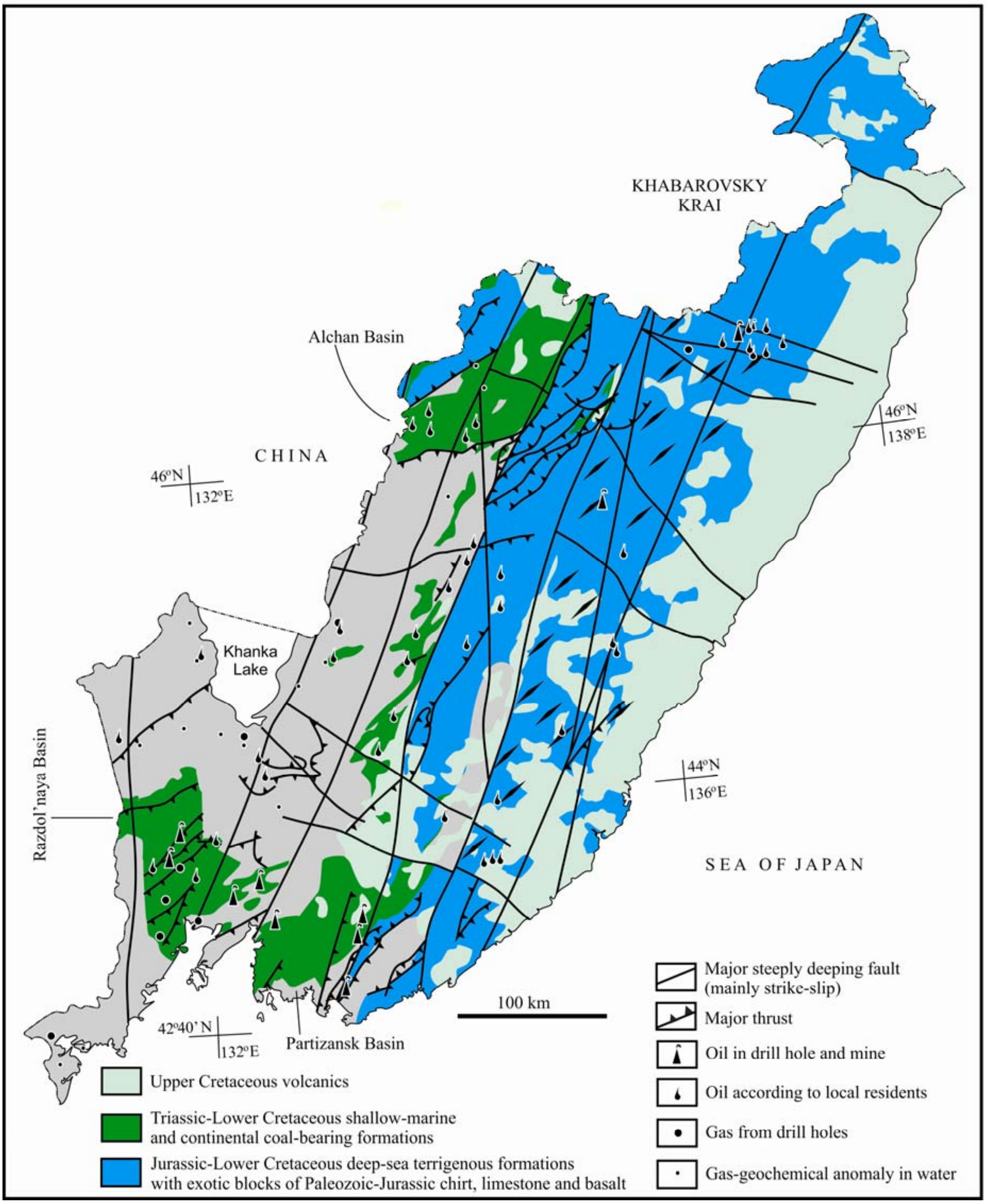

Fig. 6. Scheme of Mesozoic tectonics and sedimentary formations of Primorye showing evidence of oil and gas (after Nechaev et al., 2015).

All of the major processes during the described Cretaceous turn may be interpreted as transitional processes, related to a changing state of Earth, especially in its outer core. Here, its liquid nature is liable to react to the gravitational and electromagnetic transformations in the most dramatic manner. When the space changes came at 135-120 Ma, the turbulent flows in the outer core triggered voluminous ascending magmatic plumes associated with fluid flows, sufficient in volume to significantly transform the mantle, crust, hydrosphere, biosphere and atmosphere. The plume-supported flattening and melting of the subducted slab materials could explain the initiation of numerous adakitic melts that formed the giant East Asian Adakitic Province. These and associated juvenile events directly and indirectly produced numerous ore, coal, gas and oil deposits. This led to the Cretaceous time being one of the most commercially significant periods of geological history.

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