Open Journal of Earthquake Research, 2022, 11, 73-88
https://www.scirp.org/journal/ojer
ISSN Online: 2169-9631
ISSN Print: 2169-9623

Stress Transfer and the Impact of the India-Eurasia Collision and the Western Pacific Subduction on the Geodynamics of the Asian Continent

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How to cite this paper: Bykov, V.G. and Merkulova, T.V. (2022) Stress Transfer and the Impact of the India-Eurasia Collision and the Western Pacific Subduction on the Geodynamics of the Asian Continent. *Open Journal of Earthquake Research*, **11**, 73-88.
https://doi.org/10.4236/ojer.2022.114005

Received: October 11, 2022
Accepted: November 4, 2022
Published: November 7, 2022

Abstract

The interaction between the India-Eurasia collision and the Western Pacific subduction and their contribution to recent geodynamics of the Asian continent are discussed. We perform a comparative analysis of the data available from world literature and new data on the slow strain and earthquake migration from the India-Eurasia collision and the Western Pacific subduction zones. Based on the concepts of wave dynamics of the deformation processes, a localization scheme is constructed illustrating the migration of slow strain fronts in central and eastern Asia, and the wave geodynamic impact of collision and subduction on the Asian continent is shown.

Keywords

Stress Transfer, Earthquake Migration, Slow Strain Fronts, Geodynamics, India-Eurasia Collision, Western Pacific Subduction

1. Introduction

Recent geodynamics and seismicity of the Asian continent are governed to a significant extent by tectonic processes (collision and subduction) that occur at the convergent boundaries of the Eurasian, Indian, Amurian, Okhotsk, Pacific, Philippine and China plates (**Figure 1**).

The India-Eurasia collision zone, the deepest and most active intracontinental subduction zone on Earth, originated due to a collision between the Indian and Eurasian lithospheric plates at the western Himalayan margin. The zone incorporates the Hindu Kush, Pamir and Tian Shan orogenic systems and represents two converging subduction zones, which are the southward Eurasian plate subduction under the Pamirs down to 300 km depth and the northward Indian plate subduction beneath the Hindu Kush down to a depth of 500 km [1] [2] [3]. The Hindu Kush is also affected by the subduction of the Arabian Plate under the central Iranian Plate [4].

The Western Pacific subduction zone is known to be the most active seismic area in eastern Asia. The most powerful earthquakes are recorded here whose foci are determined to be located in relatively narrow active fault zones, namely, the Japan, Kuril and Kamchatka trench different in the extent and density of the seismic energy released and the power of the sources generating earthquakes [5]. The Pacific plate subduction beneath the Eurasian plate exhibits a discrete-translational (impulse) pattern in the Japan-Kuril-Kamchatka subduction zone [6] [7].

The horizontal compression caused by collision and progressive indentation of the Indian subcontinent into the Eurasian plate has long been assumed to play a major role in the geodynamics of eastern Asia, while the backarc basin formation in the Japan and Okhotsk Seas and in the Kuril Basin was explained by a long-range impact of this collision [8]. However, in the past two decades, convincing arguments have been proposed in favor of an active role for the Pacific subduction in the overall strain field generation in mainland Asia. For example, a comparative analysis of the long-term distribution of seismicity shows that the Pacific plate impact produced via the Korean Peninsula and northern China may likely be regarded as one of the probable causes of seismicity variations in mainland Asia [9]. In addition, it follows from mathematical modeling that the deformation processes caused by the Pacific plate underthrusting in the Kuril-Kamchatka and Japan subduction zones may serve as the sources of compression strain at the western boundary of the Amurian plate [10]. It has also been concluded from physical modeling that strain generation in mainland Asia can be controlled by the Western Pacific subduction [8] [11].

Nonetheless, the Western Pacific subduction impact on the overall strain field generation in mainland Asia has not been thus far thoroughly studied. The lack of data on the earthquake migration from the Japan and Kuril-Kamchatka trenches does not allow one to gain a deep insight into the geodynamic impact of the Pacific subduction on the Asian continent. Therefore, we studied the earthquake distribution in the Kuril-Kamchatka segment of the Pacific subduction zone and the earthquake migration toward the Asian continent in the time period from 1960 to 2015. It is necessary to clarify how the India-Eurasia collision and the Western Pacific subduction zones can produce an impact on the geodynamics of the Asian continent, *i.e.* to reveal the physical mechanism (or mechanisms) responsible for the stress transfer within the Asian lithosphere.

The concept of strain waves in the Earth, or the wave dynamics of deformation processes significantly slower than seismic ones, has been in progress in the Earth sciences in recent years. The transfer of perturbations of the stress fields affects the geological medium, geophysical fields and processes [12].

Collision, subduction and active rifting zones are the areas where the interaction between the geoblocks and lithospheric plates occurs and which are, at the same time, the intense sources of generation of slow strain waves [13]. These waves are detected from variations in seismicity and geophysical fields. Migration of seismicity is the most explicit manifestation of the geodynamic impact. Seismicity migration is suggested to be related to the propagation of slow strain waves that cause additional loading and trigger earthquakes in the faults with high concentrations of stresses.

The seismic migration processes and their features observed in different geodynamic settings have thus far been investigated in central and eastern Asia [5] [14]-[35]. The characteristic migration parameters (velocities, recurrence intervals, and energy) have been determined on the Pacific margin, which is the most tectonically active area, and the dependences of the migration velocities on the energy characteristics have been established [36] [37]. Analysis of the World Stress Map database has revealed the features and trends in the stress state dynamics of the geological medium which are displayed during the preparation of large earthquakes on the Pacific and the Japanese Island Arc margins [31], and develop our concepts on the relationship between tectonic stresses and the seismic activity.

The principal goals of the paper are as follows: 1) to give an overview and analyze the data available from the world literature on the slow strain and earthquake migration from the India-Eurasia collision and the Western Pacific subduction zones; 2) to construct a scheme illustrating the localization and migration of the strain fronts in central and eastern Asia; 3) to calculate the migration velocity of earthquakes from the Japan and Kuril-Kamchatka trenches toward the Asian continent.

2. The Impact of Collision and Subduction on the Geodynamics of the Asian Continent

In central and eastern Asia, the distribution of seismicity is governed by the overall strain field generation in mainland Asia and is directly linked to the interaction between the Indian-Eurasian plate collision and Pacific plate subduction zones. Recent geological data and GPS observations indicate the eastward motion of separate blocks to the western Pacific coast due to a collision between the Indian and Eurasian lithospheric plates [38] [39] [40] [41]. This causes strike-slip fault activation [8] [42] and, as a consequence, the directed strain and earthquake migration, which is especially explicitly observed in northern China [23] [43].

Numerical modeling suggests that the Indian-Eurasian plate interaction appears to be the main driving force for the horizontal strain to occur within the lithosphere of mainland Asia [44]. Nevertheless, the data available are evidence that in an extensive area of western China seismicity is caused not only by the India-Eurasia collision. Analysis of the seismic activity in the North-South Seismic Belt (NSB) of China indicates that the long-term seismicity variation observed in the northern NSB was induced by the geodynamic impact of the Pacific plate

[9]. Additionally, as inferred from physical modeling, the synchronous activity and the interaction between the India-Eurasia collision and the Western Pacific subduction can provide an explanation for numerous features of the strain field generated in central and eastern Asia, and the Western Pacific subduction controls strain generation in mainland Asia [8] [11].

The study of the mechanism of rifting in the Baikal Rift Zone (BRZ) contributed to better understanding of the impact produced by collision and subduction on the strain generated in central and eastern Asia. Mathematical modeling has revealed that the deformations observed near the Baikal Rift can only be explained by a joint impact of the India-Eurasia collision and the deformation processes initiated by the Pacific plate underthrusting in the Kuril-Kamchatka and the Japan subduction zones in proximity to the eastern boundaries of the Anurian plate [10]. Physical modeling of the strain transfer from the India-Eurasia collision and the Western Pacific subduction zones toward the BRZ has convincingly shown the possible passive rifting in the BRZ due to slow strain waves moving from the collision and subduction zones [11].

In summary, the seismological studies [20] [24] [32] [33] [34] [35], and the mathematical [10] and physical [11] [45] modeling results have demonstrated the impact of the India-Eurasia collision and the Pacific subduction on the geodynamics of the Asian continent.

3. Earthquake Migration and Slow Strain Waves in the India-Eurasia Collision Zone

Manifestation of slow strain waves generated due to the India-Eurasia collision were detected at the western Himalayan margin in the Pamir-Hindu Kush (or Tian Shan) seismic zone [46] [47] [48] [49].

The migration of the seismic wave velocity anomalies, which corresponds to "strain waves" traveling east to west with a velocity of an order of 33 km/yr at a period of about 3 years, was observed in the Pamir and Tian Shan junction zone in the Garm region [46]. In this region, strain wave velocity values $V = \lambda/T = 90$, 30, and 18 km/yr have been determined for the characteristic period of seismicity $T = 3$ years and wavelengths $\lambda = 270$, 90, and 54 km [47]. The velocity value of 30 km/yr is coincident with the data reported by [46] on the motion of the front of the seismic wave velocity anomalies along the continental lithosphere.

The oscillation seismicity mode observed in the northwestern Himalayan collision zone can be explained by strain wave excitation in the Pamir and Tian Shan junction zone due to discrete pattern of the lithospheric plate collision [48]. Strain wavefronts propagate here in the northern and northwestern orientations at a velocity of ~30 km/yr within the Pamir-Hindu Kush area in the south to the Garm region in the north. The velocity of these waves increases up to 100 - 120 km/yr toward the center of the northern Tian Shan. Strain wavefronts propagating at a velocity of 40 - 50 km/yr at the northeast to southwest orientation of the wavefront motion have recently been identified in the Garm region [49].

In the eastern part of the India-Eurasia collision zone, the Himalayan compression zone appears to be the source of waves of plastic deformation that initiate earthquakes in central and eastern Asia. Analysis of the spatiotemporal distribution of large earthquakes (M ≥ 7) and the field of plastic deformation has revealed two types of strain waves here, namely, "century" (T ~93.7 years) and "decade" (T ~10.8 years) waves traveling with velocities of 1 - 7 km/yr and 12 - 45 km/yr, respectively (**Figure 1**) [27] [28]. The distribution of earthquakes in mainland China is controlled by the field of plastic deformation in the lower lithosphere, which provides the energy transfer within the plate for long distances [50]. Migration of earthquakes is mostly dependent on the propagation of waves of plastic deformation [27] [28] that periodically migrate north-east thus triggering large earthquakes in the entire area of China.

In the Baikal Rift Zone located north of China, strain waves, that cause recent seismic fault activation in central Asia, have also been detected. The velocity values of these waves vary from 7 to 95 km/yr, while the wavelengths range from 130 to 2000 km [21].

In works [33] [34] [51] presented a detailed analysis of the migration of large earthquakes occurred in the 20th century in the seismic belts of central and eastern

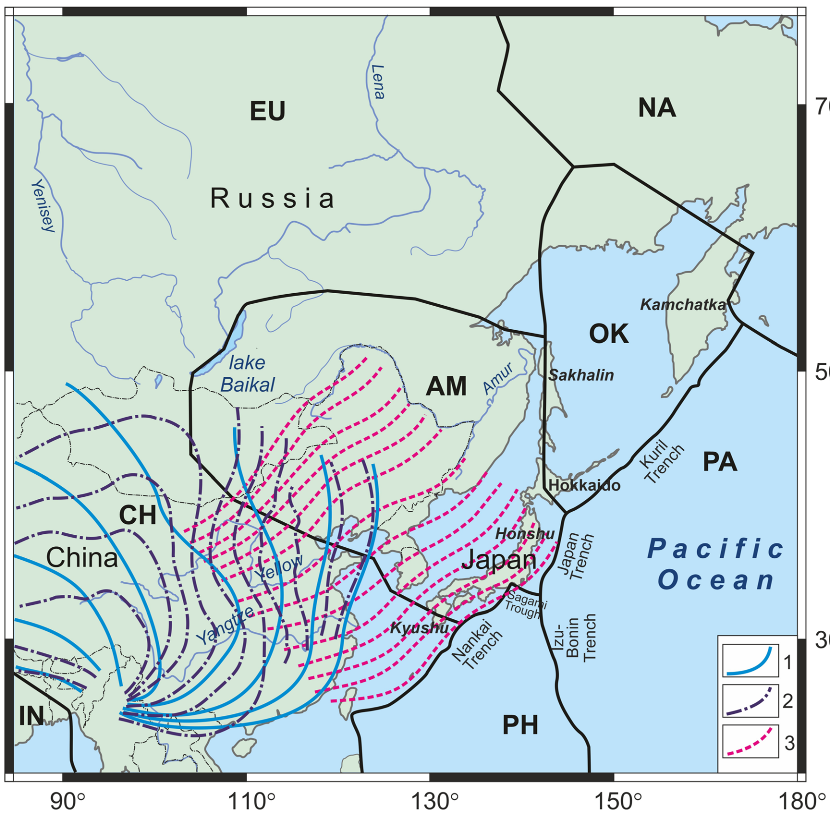

Figure 1. Localization of slow strain wave manifestation. 1: decade and 2: century waves of plastic deformation in central and eastern Asia [27] [28]; 3: strain wavefront motion from the Pacific subduction zone toward mainland China [32]. Abbreviations for lithospheric plates: EU: Eurasian; NA: North American; PA: Pacific; PH: Philippine; AM: Amurian; OK: Okhotsk; IN: Indian; CH: China.

Asia and the India-Eurasia collision zone. In mainland China, 28 earthquake migration chains have been revealed in 12 districts [33]. In eastern Asia, the highest seismic activity and migration of large earthquakes were mostly pronounced in the continental west, which was accounted for the movements in the Himalayan collision zone and adjoining structures.

In the Pamir-Baikal Belt of about 5500-km length, the epicenters of earthquakes (M ≥ 7.9) migrated southwest-northeast at a velocity of about 110 km/yr from 1907 to 1957 [33]. The migration trends for the seismicity maxima (M ≥ 5) revealed in the same belt along the Tian Shan-Baikal Rift Zone profile during 1950-2009 have been interpreted as the strain fronts moving southwest-northeast and in the opposite direction at a velocity of 90 km/yr [20]. The epicenter migration exhibited the discrete-translational (impulse) pattern, which was due to quasiperiodic generation of the strain fronts in the India-Eurasia collision zone and was in agreement with earlier results [48].

In the period from 1905 to 1950, the west-east migration of M ≥ 8 earthquakes was observed at a velocity of 55 km/yr [33]. It should be pointed out that the Pamir-Baikal (1907-1957) and the Himalayan (1905-1950) earthquake migration chains were synchronously manifested. The migration of the foci of large earthquakes (M ≥ 7.9) at a velocity of 205 km/yr was recorded in 1935-1957 for the greater part of about 4000-km long Sumatran-Mongolian Belt crossing mainland China up to western Mongolia [51].

4. Slow Strain and Earthquake Migration from the Pacific Subduction Zone Deep into the Asian Continent

Large earthquake migration along the Japan and Kuril island arc trenches [24] [29] [36] [52] and in the Pacific Seismic Belt [17] [37] has long been known and well studied.

Migration of the most powerful earthquakes (M ~8) from the trenches of the Western Pacific to mainland China was discussed by [32] [35]. This event was dramatically large-scale and lasted during 130 years (1610-1740) migrating at a velocity of about 20 km/yr for a distance of 2600 km. The migration direction was consistent with the Pacific plate subduction direction. The observed velocity of the earthquake migration in the form of the wavefronts (**Figure 1** and **Figure 2(a)**) [32] was comparable to the migration velocity of crustal deformation in Japan (10 - 100 km/yr [53] [54], and the migration velocity of earthquakes from the Japanese Island Arc to northeastern China via the Korean Peninsula (20 - 30 km/yr) [24].

In work [35] also provides convincing examples illustrating the geodynamic impact produced on the Asian continent from the side of the Pacific Ocean, and revealed the spatial and temporal distribution of earthquake migration in eastern Asia from 1600 to 1930 in different time intervals: 1600-1739, 1703-1879, and 1763-1927 (**Figure 2**). During the I-st time interval, the migration velocity varied between 14 - 22 km/yr, whereas in the II-nd interval, it ranged within 20.4 - 50 km/yr, and in the III-rd interval, it was equal to 25.2 - 62.1 km/yr.

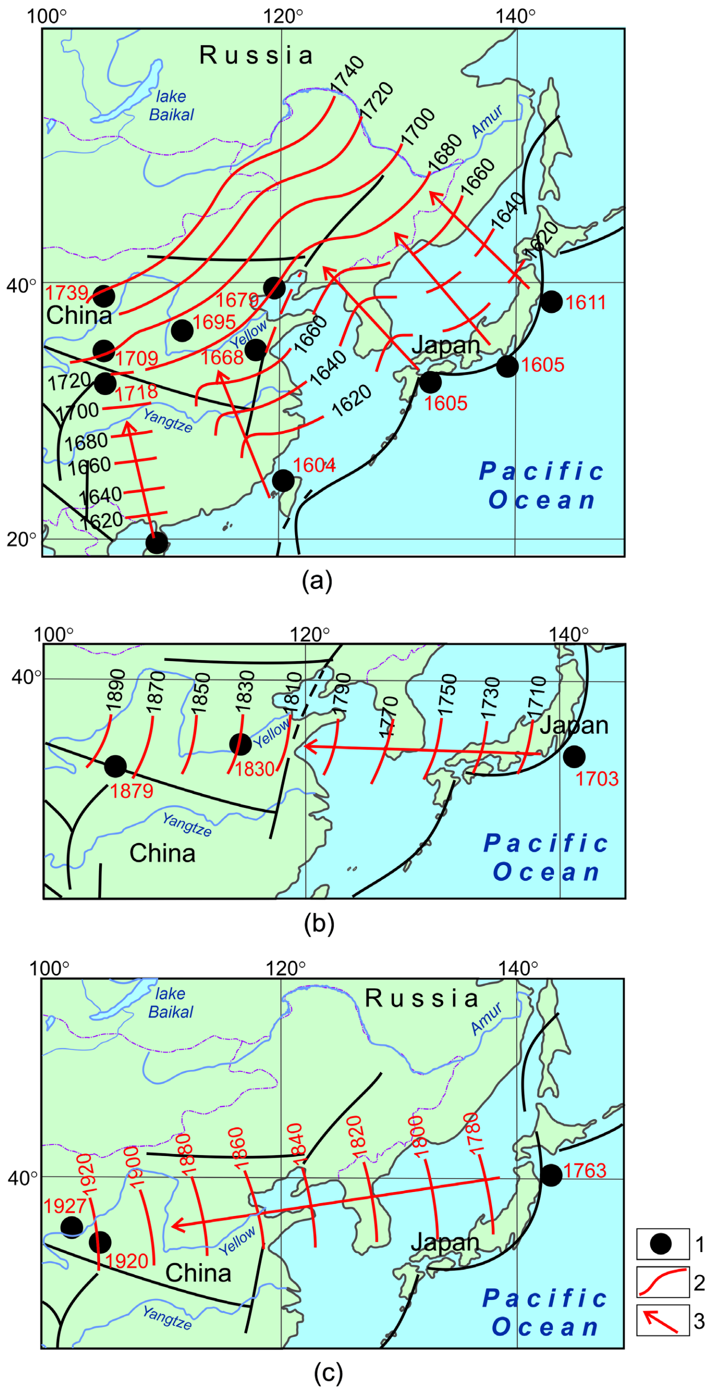

Figure 2. Migration of earthquakes from the Pacific subduction zone toward mainland China at different time intervals: (a) 1600-1739, (b) 1703-1879, and (c) 1763-1927 [35]. 1: earthquakes; 2: strain wavefronts; 3: direction of wave propagation. Figures show magnitudes and origin dates of earthquakes.

Analysis of the seismicity distribution in the regions bordering with active segments of the Pacific Belt indicates that the seismic activation behavior is often of the wave pattern and is coincident with a specific strain wavefront motion. In the Primorye and Priamurye regions (Russia), the strain fronts propagate north-west from Japan in the direction opposite to the recent motions of the Eurasian and Amurian lithospheric plates. The migration of crustal earthquakes at a velocity of about 5 - 10 km/yr is most clearly pronounced. The seismic activation is propagating from the subduction zone both toward the Asian continent and the island arc system. The vertical migration of seismicity is estimated at 50 - 60 km/yr which correlates with the velocity of global strain waves.

Migration of strain at a velocity of about 10 - 140 km/yr was revealed in different regions of eastern Asia [6] [53] [54] [55]. The migration velocity from the Japan and Izu-Bonin basins to mainland Japan was found to be different, attaining 40 km/yr (Tohoku) in the north-western orientation, and 20 km/yr (Kanto) in the east-west orientation [53]. The vertical strain maximum slowly transferred from the subduction zones toward the ocean at a velocity of 10 km/yr was observable near the Tohoku District and the Izu Peninsula, where the Pacific and Philippine plates subduct beneath the Eurasian plate [55]. In 1992-2000, strain migration from the subduction zone toward the continent at a velocity of 90 - 140 km/yr was registered by the observation network installed in Kyusyu Island [6]. In is known that in 1978-1983, the horizontal compression strain migrated at a velocity of 5.5 km/day (2000 km/yr) from the trench to the continent via Japan, the Southern Kurils and Sakhalin for about 8800-km distance [7].

5. Spatiotemporal Distribution of Earthquakes and Characteristics of Their Migration from the Japan-Kuril-Kamchatka Trench toward the Asian Continent

In Section 4, we presented an overview of the data on the migration of earthquakes from the Japan and Nankai trenches toward the continent. Here we show the investigation results on the distribution of earthquakes in the Kuril-Kamchatka segment of the Pacific subduction zone, and the recent earthquake migration from the Kuril-Kamchatka Trench toward the Asian continent, which is first discussed.

It follows from the earthquake distribution that in the Kuril-Kamchatka segment of the Pacific subduction zone the seismic events are mostly localized in the northeastern orientation and the transverse migration zones are clearly observed in some sectors. The depth distribution and migration of earthquakes have been analyzed for three profiles located in a 500-km wide band (250-km distance from both sides of the profile line) (**Figure 3**). The profile *AB* extends from the Western Pacific plate margin via the southern extremity of Hokkaido Island up to the Priamurye region. The profile *CD* runs northward, from the Pacific plate boundary via Sakhalin Island, the Lower Priamurye region and farther. The profile *EF* starts from the Kamchatka Peninsula, running via its southern termination and the Sea of Okhotsk, and reaches the coast in the area of the town of Okhotsk. The distance separating these almost parallel profiles attains about 1200 km, and the length of the profiles is estimated at 3000 - 3500 km.

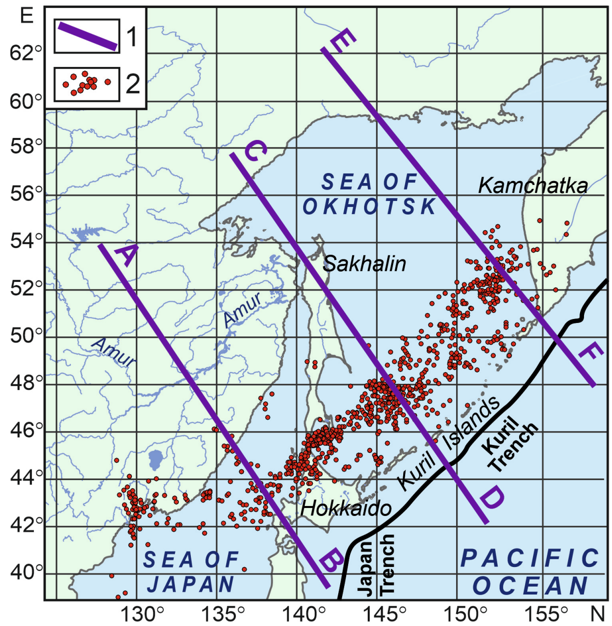

Figure 3. Locations of the study profiles showing the transverse migration of earthquakes and the distribution of M ≥ 6.0 earthquakes in the Kuril-Kamchatka segment. 1: profile locations, 2: earthquakes.

5.1. Methods

In our study, the catalog compiled at the Institute of Tectonics and Geophysics, the Far East Branch of the Russian Academy of Sciences (ITiG FEB RAS) was taken as a basis, which comprises the data on the earthquake foci borrowed from the published *Earthquakes in the USSR*, *Earthquakes in North Eurasia*, and *Earthquakes in Russia*.

To investigate the earthquake migration, the data on the $M_{LH} \geq 4$ earthquakes acquired during 1960-2015 were involved. For each profile (**Figure 3**), the hypocenter depth versus distance, the distance versus time and, additionally, the depth versus time charts were plotted for the time period of 1960-2015. Generally, the data on the earthquake origin time and location are explored to examine the earthquake migration on the continents and the migration of large earthquakes in the oceanic areas. In the present study, we involved the data on the earthquake depth to plot the depth versus time charts in order to make distinguishable the downward migration chains along the focal plane. The earthquake migration chains are only reliably distinguished in the areas where the ordered hypocenter distribution is observed matching on both depth versus time and distance versus time charts. Plotting the charts for $M_{LH} \geq 4.0$, 5.0, 6.0, and 6.5 earthquakes facilitates more reliable distinguishing of migration, which allows an additional control of the trend of ordering in the earthquake foci distribution.

To estimate the migration velocities, the regression lines were plotted on the distance versus time charts which allowed for automatic discarding of the events inconsistent with the general migration direction of the majority of the earthquakes. Actually, the calculated velocity is determined from the time interval between the first and last events in the direction of the general trend for the migration of the majority of the earthquakes. The slope of the regression line shows the displacement vector of the earthquake epicenters, whereas the tangent of slope enables determining the average velocity typical of the chain under consideration.

5.2. Results

The depth distribution of M ≥ 4 events (see **Figures 4(a)-(c)**) was constructed for each of the profiles and the distance versus time charts were plotted for M ≥ 6.5 events, which made the migration chains identifiable (**Figures 4(d)-(f)**).

On the profile *AB*, the foci of M ≥ 4 earthquakes form an inclined plane down to a depth of 510 km (**Figure 4(a)**). The earthquakes with M ≥ 6.5 form two chains, which illustrate evolving of a continentward migration process (**Figure 4(d)**). Chain 1 starts from 1960, where the migration of events is observed from a depth of 75 km to 320 km at a velocity of 15 km/yr. Chain 2 begins from 1968

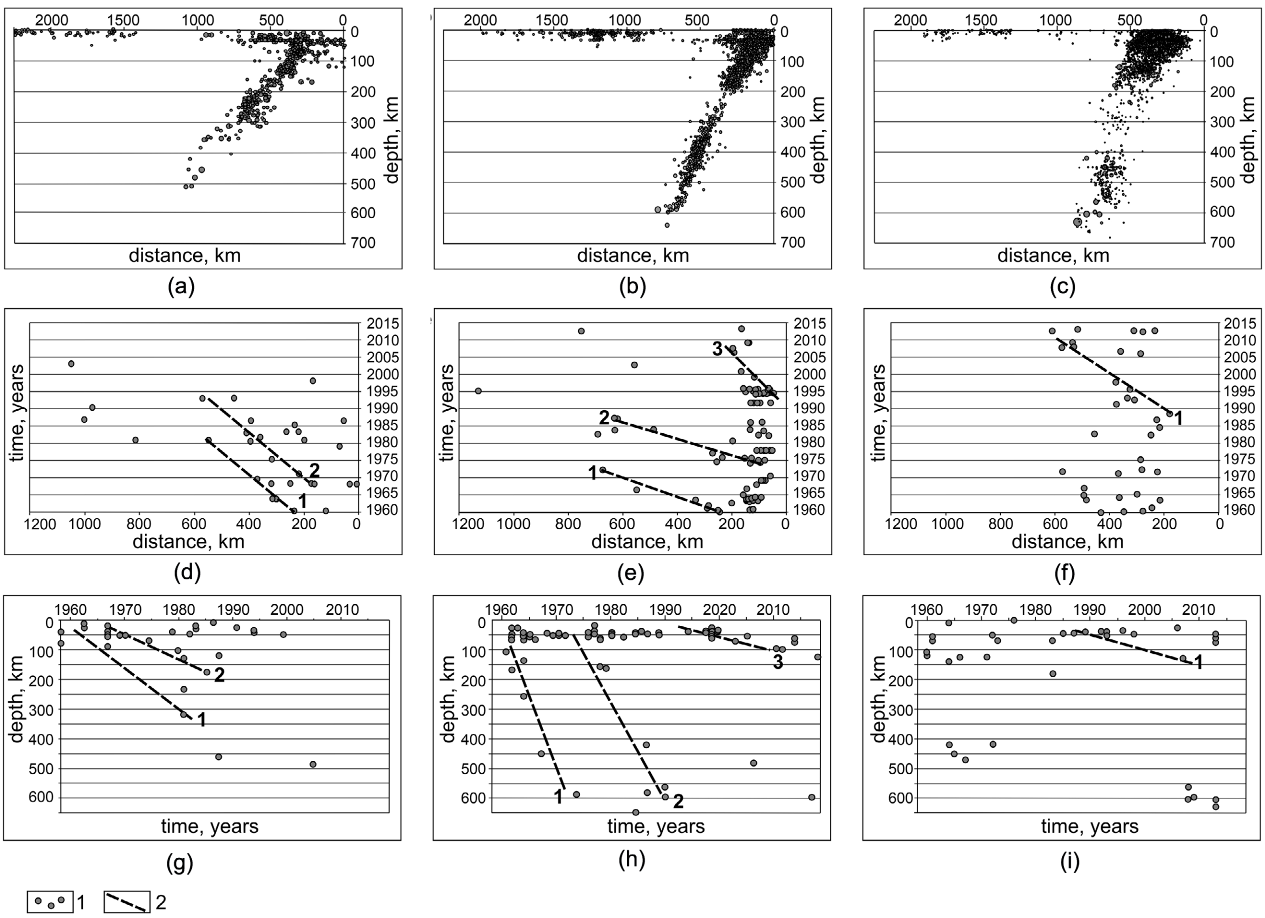

Figure 4. Earthquake distribution in the Kuril-Kamchatka subduction zone and earthquake migration chains directed toward the continent. (a)-(c) Distribution of earthquakes with M ≥ 4 along profiles *AB*, *CD*, and *EF*, respectively; (d)-(f) Time versus distance charts for earthquakes with M ≥ 6.5 along profiles *AB*, *CD*, and *EF*, respectively; (g)-(i) Time versus depth charts plotted for earthquakes with M ≥ 6.5 along profiles *AB*, *CD*, and *EF*, respectively.

(migration velocity of 15 km/yr) and propagates from the surface down to a depth of 170 km (**Figure 4(g)**).

On the profile *CD*, the earthquake localization exhibits an inclined pattern down to a depth of 600 - 640 km (**Figure 4(b)**). Here 3 migration chains of the M ≥ 6.5 earthquake foci are observed (**Figure 4(e)**), which demonstrate a continentward migration process evolving at different depths. Chains 1 and 2 begin from 1960 and 1974, exhibiting the migration velocities of 38 and 40 km/yr, respectively. In these cases, the migration starts from depths of 100 and 60 km and propagates in an inclined manner down to a depth of about 600 km (**Figure 4(h)**). Chain 3 shows similarly directed migration, but only at depths of 40 - 120 km (migration velocities of 13 km/yr).

The earthquakes located along the profile *EF* are observed down to a depth of almost 700 km (**Figure 4(c)**). As seen on the profile, at the time interval of 1988-2012, the earthquakes migrate toward the Okhotsk coast at a velocity of 29 km/yr, the depth ranging from 40 km to 150 km (**Figure 4(f)** and **Figure 4(i)**).

To summarize, the distinguished migration chains of M ≥ 6.5 large earthquakes are in agreement with the earthquake migration directed from the Pacific subduction zone toward the Eurasian continent, and their migration velocities vary within 13 - 40 km/yr. The continent ward migration of earthquakes is directed downward along the inclined plane to a depth of 600 km. The profile *AB* crossing Hokkaido Island shows the earthquake migration at a velocity of 15 km/yr, which is consistent with the velocity of migration from the Nankai Trench (20 - 22 km/yr) [32], adjacent to the Japanese Archipelago, and the velocity of migration from the Japanese Island Arc to northeastern China via the Korean Peninsula, which is approximately estimated at 20 - 30 km/yr [24]. The velocity of the earthquake migration from the Kuril-Kamchatka Trench observed at different depths of the profile *CD* exhibits values ranging from 13 to 40 km/yr. The Kamchatka Peninsula-Okhotsk profile (*EF*) shows the earthquake migration estimated at 29 km/yr.

6. Conclusions

In the present study, we applied the available data on the slow strain and earthquake migration from the India-Eurasia collision and the Western Pacific subduction zones to explore the impact of these tectonic processes (collision and subduction) on the geodynamics of the Asian continent using our calculation results, and have analyzed the earthquake distribution in the Kuril-Kamchatka segment of the Pacific subduction zone and the earthquake migration toward the Asian continent.

The main findings are as follows:

1) The India-Eurasia collision and the Western Pacific subduction zones produce a significant impact on the geodynamics of the Asian continent. The interaction between the Eurasian and Indian plates generates the meridionally oriented earthquake sequences on the Asian continent, while the Western Pacific subduction produces the sublatitudinally oriented earthquake sequences.

2) Based on the concepts of wave dynamics of the deformation processes and using the datasets available from the world literature on the slow strain and earthquake migration, we have constructed the scheme illustrating the localization and migration of the strain fronts in central and eastern Asia.

3) We have investigated the earthquake distribution in the Kuril-Kamchatka segment of the Pacific subduction zone and performed the migration velocity calculations for recent ($M \geq 6.5$) earthquakes from the Japan and Kuril-Kamchatka trenches toward the Asian continent. The calculation results are in good agreement, in terms of the migration velocity and direction, with the data on the migration of earthquakes from the Nankai Trench (20 - 22 km/yr) and from the Japanese Island Arc to northeastern China (20 - 30 km/yr).

4) We have obtained new evidence, that the Western Pacific subduction zone actually produces a significant impact on the geodynamics of the entire Asian continent. The earthquake migration suggests the wave mechanism of this geodynamic impact. We assume that this wave mechanism is the most reasonable physical mechanism capable of transferring tectonic stresses and strain for long distances from the collision and subduction zones.

Acknowledgements

The study was performed within the framework of the State Assignment for the Kosygin Institute of Tectonics and Geophysics, Far East Branch, Russian Academy of Sciences (AAAA-A18-118020790043-9).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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