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Geomorphology of the Central Kamchatka Depression, the Kamchatka Peninsula, NE Pacific

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\section*{ABSTRACT}

The Kamchatka Peninsula lies on the eastern active margin of Eurasia, adjacent to the Kuril-Kamchatka subduction zone. In this study, we provide a geomorphological map of the Central Kamchatka Depression – the largest sedimentary basin in Kamchatka and also in all the island arcs of the North Pacific. The depression extends along Kamchatka at latitudes \(\sim 44-46^\circ\) N for more than 400 km and is up to 100 km wide. The geomorphological map of the Central Kamchatka Depression is designed at a scale of 1:500,000 and contains \(\sim 3000\) mapped objects. Volcanic and tectonic landforms have been collected from published sources and generalised to the map scale. Glacial and fluvial landforms have been mapped using remote sensing data and field geomorphological surveys. Areas of ambiguous interpretation have been outlined. This map is the most detailed geomorphological map published for this region that may guide further geomorphological and paleogeographical investigations.

\section*{1. Introduction}

The Kamchatka Peninsula lies on the eastern active margin of Eurasia, adjacent to the Kuril-Kamchatka subduction zone. The successive accretion of island arc blocks that occurred here during the Cenozoic (e.g. Avdeiko \textit{et al.}, 2007; Konstantinovskaya, 2003; Lander & Shapiro, 2007) has created a unique topography of Kamchatka (Figure 1). It took its modern shape due to the shift of the subduction zone oceanward after docking of the Kronotsky arc about 2–10 Ma (Lander & Shapiro, 2007) and subsequent slab rollback (Kozhurin & Zelenin, 2017). The peninsula is up to 400 km wide, much wider than the typical island arc, and has a system of mountain ranges running along the peninsula: the Sredinny Range and the Eastern Ranges, separated by the Central Kamchatka Depression. The volcanoes of Kamchatka comprise two arc-parallel belts (Figure 2): The Sredinny Range and the Eastern Volcanic Belt. The Central Kamchatka Depression has dimensions of \(\sim 400 \times 100\) km, making it the largest drainage basin in the northern and western Pacific island arcs and one of the largest drainage basins in the Pacific island arcs. As a tectonic structure, it is an asymmetric graben with a downthrown eastern flank. It was formed no earlier than the Miocene (Avdeiko \textit{et al.}, 2007) and is now overlapped by the northern segment of the Eastern Volcanic Belt.

Extensive geomorphological studies were carried out here in the mid-twentieth century (Braitseva \textit{et al.}, 1968; Kamchatka, Kurile and Commander Islands, 1974; Kuprina, 1970; Kushev & Liverovsky, 1940). These studies accurately described sedimentary facies and provided local geomorphological schemes but lacked radiometric dates. Instead, their findings were based on the relative age of landforms and the model of glaciations developed for Eastern Europe. In addition, the geographical location of the studied objects and large-scale maps of all kinds were classified information in the USSR.

Since then, many research papers have significantly added to the earlier geomorphological works, although most of the papers were focused on volcanic geomorphology (e.g. Inbar \textit{et al.}, 2011; Ponomareva \textit{et al.}, 2006; Shevchenko \textit{et al.}, 2015; Wallace \textit{et al.}, 2022) or active tectonics (e.g. Geist & Scholl, 1994; Heinlein, 2013; Kozhurin \textit{et al.}, 2006; Podoja \textit{et al.}, 2013; Pinegina \textit{et al.}, 2013). In recent years, quantitative approaches were applied in studies of fluvial (Chalov \textit{et al.}, 2017; Romanescu \textit{et al.}, 2017) and glacial (Barr & Spagnolo, 2013; Savoskul & Zech, 1997) dynamics. However, few studies (Barr & Clark, 2012; Barr & Solomina, 2014) produced regional-scale geomorphological models.

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\section*{SUPPLEMENTAL DATA}

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2. Study area

In this study, we have mapped the Central Kamchatka Depression – the largest sedimentary basin in Kamchatka. It extends along Kamchatka at latitudes ~44–46° N for more than 400 km and is up to 100 km wide. As a tectonic structure, the Central Kamchatka Depression is a half-graben – an asymmetric basin with active normal faults of the East Kamchatka Fault Zone forming its eastern boundary (Figure 2). There are many estimates for an age of the Central Kamchatka Depression, which generally fall between the Eopleistocene (the Calabrian) (Ozornina, 2011) and the Miocene (Avdeiko et al., 2007), and the Central Kamchatka Depression is still submerging. The Central Kamchatka Depression is bounded by mountain ranges ~2 km higher than the depression floor (Figure 3) and is filled with more than 600 m of Quaternary deposits (Kamchatka, Kurile and Commander Islands, 1974); a few inselbergs rise above the Central Kamchatka Depression floor in its southern part.

The most prominent landscape features of Kamchatka are active volcanoes. The largest and most productive volcanoes of the Kamchatka Peninsula are located in the north of the Central Kamchatka Depression (Ponomareva et al., 2007), where the Eastern Volcanic Belt shifts westwards: the composite Shiveluch volcano and the Kliuchevskoi Volcanic Group (Figures 2, 3). The oldest known dates for rocks of the Kliuchevskoi group are 262–274 ka (Calkins, 2004), whereas no rocks older than 100 ka have been found at Shiveluch (Pevzner et al., 2014). Apart from these volcanoes, the Early Pleistocene Nikolka volcano (Ermakov & Bazhenova, 2018) is the only large volcanic ediifice in the Central Kamchatka Depression.

Surface processes in Kamchatka are typical for the boreal zone. The depression is drained by the Kamchatka River and its tributaries (Figure 3), so most of its floor is an area of modern fluvial processes. The mountain ranges around the depression protect it from cold and humid maritime air and create more continental conditions. Modern glaciers in the CKD
are therefore confined to the highest volcanic edifices and have little impact on the landscape.

The palaeogeography of the region is still highly ambiguous. The extensive geomorphological and stratigraphical studies of Kamchatka in the mid-twentieth century followed the scheme of Eastern European glaciations. Although no Middle or Early Pleistocene glacial landforms were identified within the Central Kamchatka Depression, detailed models were developed for the Last Glacial Period, which included two...
phases: a Phase I ice cap and a Phase II piedmont glaciation; however, the tentative extent of these glaciers was only shown on small-scale maps (Braitseva et al., 1968; Kamchatka, Kurile and Commander Islands, 1974). A few subsequent palaeogeographic studies of the Late Pleistocene deposits and landforms (e.g. Barr & Clark, 2012; Barr & Solomina, 2014; Kraevaya & Kuralenko, 1983; Ponomareva et al., 2021) have added to the temporal and geographic context of these models, but the spatial detail has not been improved since the first studies.

3. Methods

Mapping was carried out in the UTM Zone 57N coordinate system on the WGS1984 datum (ESPG 32657) at a spatial scale of 1:100,000 to 1:200,000; the final map has a scale of 1:500,000. ArcGIS 10.5 and QGIS 3.28 Firenze were used for the mapping, and CorelDRAW X7 was used for the layout design. The 2-m resolution ArcticDEM digital terrain model (https://www.pgc.umn.edu/data/arcticdem/) was the primary source for mapping, supplemented by the SRTM 1 arc-second global digital elevation model projected to 25-m resolution and a cloudless mosaic of Sentinel-2 imagery (10-m resolution). Geomorphological interpretations were verified by field surveys.

The background image is compiled from the hillshaded HydroSHEDS Void-filled DEM (https://www.hydrosheds.org), GSHHG shoreline (https://www.soest.hawaii.edu/pwessel/gshhg/), GEBCO bathymetry (https://www.gebco.net/data_and_products/gridded_bathymetry_data/), rivers and modern glaciers (both manually digitised from topographic maps).

The mapping area included the Central Kamchatka Depression as a tectonic structure, with its boundaries traditionally confined to the extent of sedimentary fill (Kamchatka, Kurile and Commander Islands, 1974). Due to the ambiguity of its western boundary, the mapping also included tributary valleys that cut into the Sredinny Range. In this study, the Shchapina (or Shchapinsky) and Azhabachye Lake grabens

Figure 3. The topography of the Central Kamchatka Depression. Red lines, active faults (Kozhurin & Zelenin, 2017); red asterisks, major Holocene volcanoes (Ponomareva et al., 2007); black boxes, location of Figure 4. Tectonic highlands that bound the depression from the north and inselbergs within its floor are shown with grey tint.
(Figure 2) at the eastern boundary of the depression were not considered.

The mapping strategy was based on the current state of knowledge, which varies considerably between landform classes. The mapping started from well-documented volcanic and tectonic landforms, then the area of modern fluvial processes was outlined, thus bracketing the landforms at intermediate elevations. Details of the mapping approach for each identified class are given below. The age classification follows the formal stages of the Quaternary with a separate class of ca. 11.7–30 ka roughly corresponding to the global Last Glacial Maximum and the Late Glacial. Landforms of uncertain age or origin are indicated.

4. Genetic classes of landforms

4.1. Tectonic landforms

The Central Kamchatka Depression is an actively developing tectonic depression with an extremely high tectonic activity concentrated at faults of its eastern boundary (Figure 2) with an average rate of horizontal slip reaching 13 mm/yr (Kozhurin & Zelenin, 2017). Active faults in Kamchatka have been extensively studied (Geist & Scholl, 1994; Kozhurin et al., 2006, 2014; Legler & Parfenov, 1979; Zelenin et al., 2020, 2022). The spatial detail of published fault patterns is good enough to be reproduced from the sources. In most cases, they represent fault scarp, which occur when a fault plane crosses the Earth’s surface. Although areas of tectonic subsidence were implied in these geodynamic models (vertical arrows on Figure 2 B, C), the deformation gradually decreases away from the fault zones without a specific boundary.

Although the reported thickness of the depression fill reaches 600 to 1000 m (Kamchatka, Kurile and Commander Islands, 1974; Ozornina, 2011), several bedrock inselbergs rise above its floor. They are all located in the narrow oblique belt in the south, resembling the western wall of the Shchapina Graben. However, the active uplifting was supposed only for the largest one, the Generalka Uplift (Kamchatka, Kurile and Commander Islands, 1974). Bedrock uplands within the Central Kamchatka Depression are confined to stepovers of the East Kamchatka Fault Zone and therefore have intermediate heights between the CKD floor and the Eastern Ranges. In the north, bedrock uplands trace the northern boundary of the CKD. We consider these inselbergs and uplands as tectonic landforms due to tectonic origin of their spatial distribution (Figure 3).

4.2. Volcanic landforms

The volcanoes of Kamchatka have been the subject of many studies. Among the landforms of Kamchatka, volcanic landforms are the best constrained in space and time. For mapping, we first reviewed the inventories of Holocene volcanic centres provided by Ponomareva et al. (2007) and the Holocene Volcanism of Kamchatka database (http://geoportal.kscnet.ru/volcanoes/geoservices/hvolc.php). Relevant maps were collected for the Holocene volcanoes of Shiveluch (Gorbach & Portnyagin, 2011; Ponomareva et al., 2014), Kliuchevskoi (Khrenov et al., 2002) and Plosky (Ponomareva et al., 2013). Lava sheets of the Tolbachik monogenetic lava field is shown after Churikova et al. (2015).

Pleistocene volcanism in Kamchatka is much less studied. Data for the Kliuchevskoi Volcanic Group have been summarised by Churikova et al. (2015), allowing the classification of its volcanic centres by age. Absolute dates have been reported for all other major volcanic edifices in the Central Kamchatka Depression: Old Shiveluch (Pevzner et al., 2014), Kharchinsky and Zarechny (Ponomareva et al., 2021; Volynets et al., 1999), Nikolka (Ermakov & Bazhenova, 2018). No age estimates are available for the pre-Holocene monogenetic vents of the Sredinny Range. However, the northernmost of them are attributed to the same volcanic complex as the Holocene vents (Gorbach et al., 2021) and may not be significantly older.

The gathered data and the map scale suggest the following classification of volcanic landforms: volcanic edifices, talus of debris avalanches or pyroclastic density currents, and lava fields. Adjacent objects of the same class have been merged together to simplify the presentation. The resulting dataset comprises 107 objects with a total area of ca. 8 000 km² (30% of the total mapped area), mostly located in the Kliuchevskoi Volcanic Group.

4.3. Fluvial and lacustrine landforms

These landforms comprise a series of steps, most diverse in the middle reaches of the Kamchatka River.

The floodplain is mapped relying on geochronological, historical, and morphological evidence. Tephrochronological (Pevzner et al., 2006) and radiocarbon (Karimov et al., 2020) dating yielded late Holocene age of the floodplain deposits. Historical data for the twenty-first century (https://allrivers.info) provides maximum flood levels of about 7 m in the middle reaches of Kamchatka, at the settlement of Dolinovka, and about 5 m at the settlement of Kozyrevsk. These criteria confine the extent of the floodplain to a belt of free meandering (Figure 4A) or braided channels (Figure 4B) – a clear morphological indicator.

Terraces along the Kamchatka River and its major tributaries form two levels of parallel steps that slope downstream at heights 10–110 m above the channel (Figure 4A). All these levels are covered by a full
Holocene sequence of tephra layers. Some of the outcrops of the lower level were studied by Ponomareva et al. (2021) and dated back to the Last Glacial Maximum and Late Glacial. These terraces rise for 10–50 m above the channel and form up to three steps, which cannot be traced along the Kamchatka valley and may represent local tectonic deformations. The abandoned river valleys of the same height, related to stream avulsion in alluvial fans, were mapped together with these terraces. The upper level of the terraces forms modern flat watersheds between the major tributaries of the Kamchatka River. It has a more uniform height of 70–110 m above the floor of the valleys tending to lower downstream. No absolute dates have been published for them, but a lower lacustrine part of their outcrops, the ‘blue clays’ unit, is attributed to the Middle Pleistocene interglacials (Braitseva et al., 1968). Although the topography of all the terraces

Figure 4. Examples of mapped landforms at the scale of mapping (note the different scale and hypsometric tints of the schemes). 

A, a sequence of terraces in the middle reaches of the Kamchatka River. 

B, broad floodplain with braided channels in the lower reaches of the Kamchatka River, bounded by volcanic debris talus together with moraines and debris avalanches in the north, and lava flows in the south (note the absence of kettles and higher hummocks in the debris avalanche comparing to moraine). 

C, alluvial fans at the tectonic boundary of the Central Kamchatka Depression; each fan apex is located at the mouth of a mountain valley, active fan is deeply incised into the inactive fans and reaches the floodplain further north. 

D, spatial relation of glacial landforms in the western Central Kamchatka Depression: the most recent moraine of the Last Glacial Maximum fills the mountain valley, an outwash plain is sloping off the Last Glacial Maximum terminal ridge, elevated portions of older moraines survived at some slopes of the Sredinnny Range. 

E, the Last Glacial Maximum moraine at the Kliuchevskoi Volcanic Group (the Pakhcha valley), partially eroded and buried by the volcanic debris talus.
suggests a fluvial origin, a large contribution of lacustrine sedimentation has been described in some of their sections (Kuprina, 1970; Ponomareva et al., 2021). However, these data are not sufficient to map lacustrine and fluvial terraces separately.

Alluvial fans were mapped where cones of alluvium that spread out from the mountain valleys to the lowlands of the Central Kamchatka Depression. They have a convex fan shape with a network of shallow braided streams on their surface not confined to a single valley. Even when individual fans merge into a continuous apron, there is a clear connection between a fan apex and a mouth of its source valley (Figure 4C). Several generations have been identified in the largest fans, with active segments cut into inactive fossil fans. When joining valleys of Kamchatka or its major tributaries, these inactive fans are toe-trimmed by lateral erosion, whereas the active fans spread above the floodplain. Apart from fluvial fans, similar landforms at active volcanoes have been mapped as volcanic debris talus. Volcanoes provide a greater flux of loose sediments and favour debris flows, creating a vast and rapidly evolving apron around volcanic edifices (Figure 4B, E). One more subdivision of alluvial fans is distal fan plains that form terrace-like landforms, extremely low and flat. They are flooded during the snowmelt and therefore could be attributed to the floodplain. However, unlike the floodplain, they bear no signs of past channels and are associated with the outer edges of unconfined alluvial fans. Their vast extent in the north of depression with size of individual bodies reaching 100 km² may suggest a subaqueous deposition similar to deltaic bottomsets.

4.4. Glacial landforms

The chronology of glaciations in Kamchatka is poorly known and suggested to differ from the global ice volume changes (Barr & Solomina, 2014). The moraine of the Last Glacial Maximum was dated in the Kluchevskoi Volcanic Group at the sequence of outcrops along the Pakhcha River (Kraevaya & Kurilkenko, 1983; Ponomareva et al., 2021), which record two advances of glaciers during 12–30 ka. This moraine expresses a classic complex of hummocky topography bounded by end moraine ridges (Figure 4C-E). Moraines with such morphological signatures are typical for morphologically young cirques and trough valleys with a clear correlation with latitude. These moraines have been mapped as end moraine complexes of the Last Glacial Maximum. On active volcanoes, debris avalanches may produce topography similar to moraine (e.g. Paguican et al., 2021). In Kamchatka, debris avalanches are able to create larger hummocks (reaching 100 m in height at Shiveluch piedmont) with flat surface between them and rare kettles; their reported runoff (Ponomareva et al., 2006) is much shorter than for piedmont glaciers. However, debris that fall onto the glacier body may form transitional landforms, which we arbitrarily attribute to debris avalanches.

Moraines that precede the Last Glacial Maximum are much more eroded. Only a few terminal moraine ridges survived in the valleys of the Sredinny Range. Some areas of drumlin-like hills, which we interpret as base moraine preceded the Last Glacial Maximum, remain on the depression floor, mostly in its southern part. The spatial distribution of the mapped landforms suggests that they have originated from at least two peaks of glaciation significantly different in extent and thus cannot be attributed to one penultimate glaciation.

Glaciofluvial landforms have been mapped separately from the fluvial terraces and fans as they originate from a broad front of terminal moraines (Figure 4C); therefore, glaciofluvial outwash plains and terraces can be attributed to the climatic stages. Glaciofluvial origin can be identified only for landforms adjacent to end moraines, but further field studies may reconsider some fluvial terraces as glaciofluvial.

5. Discussion

The most striking feature of the map is the dominance of late Quaternary landforms. The terrain of the Central Kamchatka Depression is extremely young, with few patches of Middle Pleistocene landforms. The Quaternary fill of the depression reaches 600 to 1000 m (Braitseva et al., 1968; Ozornina, 2011), suggesting a steady trend of accumulation during the Quaternary. The steps in the Central Kamchatka Depression topography represent the most recent changes in a base level of erosion. There are no regional-scale levels that could be related to global climatic events. Therefore, these local patches may originate from either local variations in tectonic subsidence rates or drainage avulsion. Other surface processes are unlikely to create such a diverse pattern of terraces.

Volcanic landforms have remained in the Central Kamchatka Depression since the Middle Pleistocene. The extent of modern volcanism generally inherits the location of these oldest remnants, which means that the location of the northern Eastern Volcanic Belt has been stable since its formation in the Pliocene (Avdeiko et al., 2007).

Vast extent of late Quaternary landforms indicates ongoing tectonic subsidence of the depression. A few survived inselbergs form a pattern that is unlikely to be created by sole erosion. Except for volcanic areas, the boundary between the ‘young’
landforms (the floodplain, low terraces and associated alluvial fans) and the ‘old’ landforms (high terraces and inselbergs) outlines a series of narrow depressions at the eastern boundary of the Central Kamchatka Depression (Figure 2). The tectonic origin of the northernmost one, the Shchapina graben, has been reported in geological studies (Legler & Parfenov, 1979). The southern one, the Kayvycha–Kitilgina basin, has never been interpreted as a graben, although active normal faults, antithetic to the main plain of the East Kamchatka Fault Zone, have been mapped on its floor (Legler & Parfenov, 1979; Kozhurin et al., 2006).

This mapping study made it possible to outline the location of landforms of ambiguous origin. Most of them are volcanic landforms that lack absolute dates, so the map present their relative age, which is subject to change. One more area is the southern foothills of Shiveluch where aprons of the largest debris avalanches gradually transforms into moraine complex (see section 4.4).

6. Conclusion
In this study, we have mapped landforms of the Central Kamchatka Depression – the largest sedimentary basin in Kamchatka and all the island arcs of the North Pacific. The geomorphological map of the Central Kamchatka Depression is produced at a scale of 1:500,000 and contains ~3000 mapped objects. Volcanic and tectonic landforms have been collected from published sources and generalised to the scale of the map. Glacial and fluvial landforms have been mapped using remote sensing data and field geomorphological surveys.

The map clearly shows that the Central Kamchatka Depression is extremely young, with most of its topography emerged in the Late Pleistocene and the Holocene. Rivers that drain the depression did not form regional levels of terraces that could be related to global climatic events. Instead, local steps may originate from either local variations in tectonic subsidence rates or drainage avulsion. The oldest landforms in the Central Kamchatka Depression, high terraces and inselbergs, bound tectonic grabens within the depression floor. The presented map revealed areas that lacked data on age or origin of the landforms; these gaps in geomorphic data may focus further studies. Of them, dating and differentiating of glacial landforms preceding the Last Glacial Maximum is a major challenge, which is still hampered by remoteness and isolation of a landmass of Kamchatka. The presented map is the most detailed geomorphological map published for this region, which may guide further geomorphological and paleogeographical investigations.

Software
Mapping was carried out using ArcMap 10.5 and QGIS 3.28 Firenze. The final design was completed using CorelDRAW X7.

Disclosure statement
No potential conflict of interest was reported by the author(s).

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