Gondwana Research 35 (2016) 305–322

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

# The De Long Islands: A missing link in unraveling the Paleozoic paleogeography of the Arctic

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ARTICLE INFO

*Article history:*
Received 28 December 2014
Received in revised form 16 May 2015
Accepted 18 May 2015
Available online 26 June 2015

Handling Editor: A.R.A. Aitken

*Keywords:*
De Long Islands
New Siberian Islands
Arctic
Early Paleozoic
Paleogeography

ABSTRACT

The vast Laptev and East Siberian shelves in the eastern Russian Arctic, largely covered by a shallow sea and buried beneath sea ice for 9 months of the year, remain one of the least studied parts of continental crust of the Earth and represent a big unknown when performing pre-Cenozoic reconstructions of the Arctic. The De Long Islands provide an important window into the geology of this area and are a key for understanding the Early Paleozoic history of the Amerasian Arctic. Four of them (Jeannette, Henrietta, Bennett and Zhokhov islands) were studied using structural data, petrographic and geochemical analyses and U–Pb zircon age dating to offer the following new constraints for the Early Paleozoic paleogeography of the Arctic realm. The basement beneath the De Long Islands is of Late Neoproterozoic to earliest Cambrian age, about 670–535 Ma. In the Early Paleozoic, the De Long Islands were located along the broad Timanian margin of Baltica, with a clastic sediment provenance from the Timanian, Grenville–Sveconorwegian, and Baltic Shield domains. The Cambro-Ordovician volcaniclastic successions on Jeannette and Henrietta islands formed part of a continental volcanic arc with a corresponding back-arc basin located to the south (in present co-ordinates). On the continent-ward side of the back-arc basin, shallow marine shelf clastic and carbonate rocks were deposited, which are exposed today on Bennett Island in the south-west of the archipelago (in modern coordinates). The De Long Islands together with other continental blocks, such as Severnaya Zemlya, Arctic Alaska–Chukotka, and the Alexander Terrane, formed the contiguous active continental margin of Baltica during the Early Paleozoic. Today however, these terranes are spread out over a distance of 5000 km across the Arctic and eastern Pacific margins due to the subsequent opening of a series of Late Paleozoic, Mesozoic and Cenozoic oceanic basins.



## 1. Introduction

Despite an increasing interest in the geology of the high Arctic region in recent years for its potentially significant volume of undiscovered hydrocarbon resources (Lane, 1997; Embry, 1998; Lawver et al., 2002; Miller et al., 2006; Lorenz et al., 2008; Amato et al., 2009; Miller et al., 2010; Colpron and Nelson, 2011; Lemieux et al., 2011; Anfinson et al., 2012a,b; Beranek et al., 2012; Ershova et al., 2013,; Lorenz et al., 2013; Prokopiev et al., 2013; Ershova et al., 2015a,b,c) the Russian Arctic shelves remain little studied. Geological studies here are particularly problematic as these shelves are covered by extensive shallow seas, which are frozen for 9 months of the year. As a consequence of lacking infrastructure and the remote location, deep offshore drilling is expensive and difficult and hence deep wells were not drilled to date. The scattered islands which expose small segments of the shelves are the main source of geological information, offering discrete windows into the geology of this frontier region and key-information for piecing together the enigmatic geological history of the Eurasian high Arctic. One of these high Arctic archipelagos, the New Siberian Islands, is located in the eastern part of the Russian Arctic on the border between the Laptev and East Siberian seas and exposes Paleozoic and Mesozoic strata (Fig. 1). This archipelago consists of three island groups: the Anzhu Islands (Kotel'ny, Bel'kovsky and Novaya Sibir islands) in the center, the Lyakhovsky Islands in the south close to the Siberian mainland (Malyi Lyakhovsky and Bolshoy Lyakhovsky islands), and the small De Long Islands in the far north (Jeannette, Henrietta, Bennett, Zhokhov and Vil'kitskiy islands).

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http://dx.doi.org/10.1016/j.gr.2015.05.016
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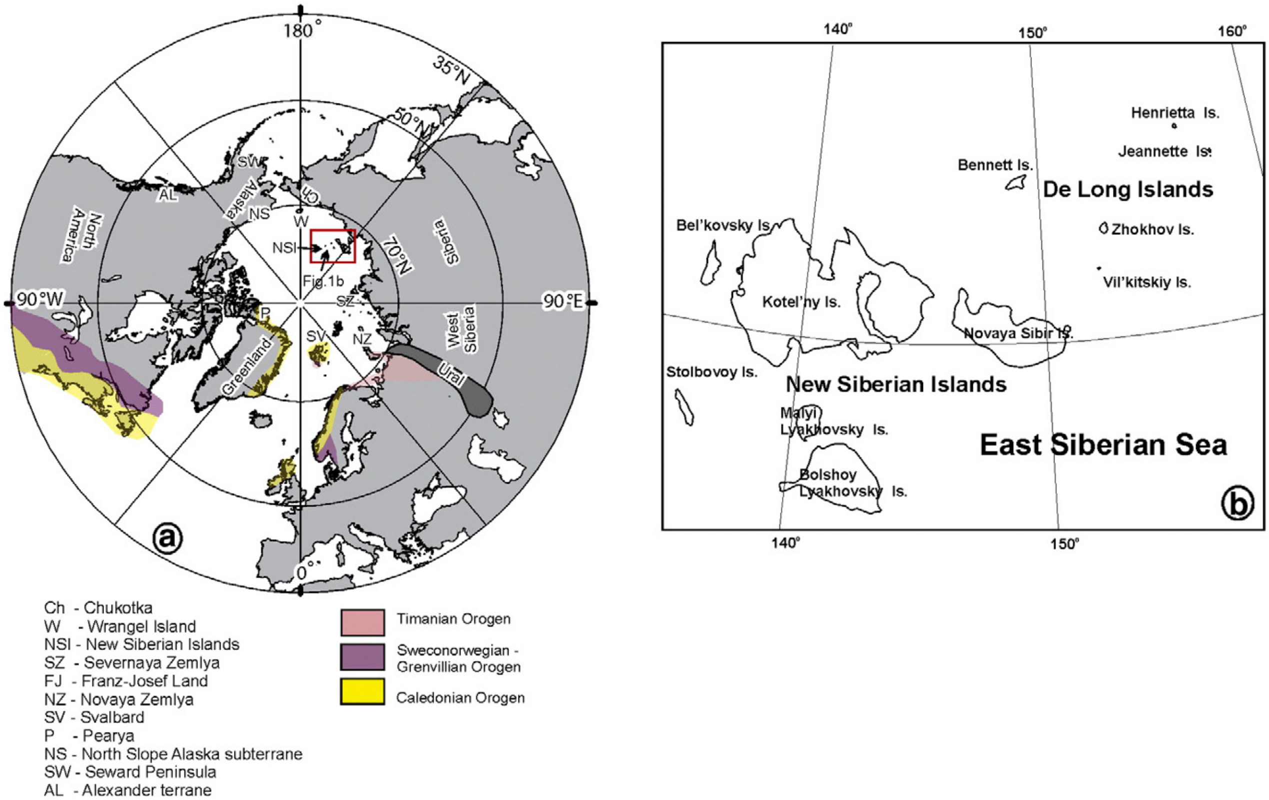


**Fig. 1.** (a) Regional setting of the study area; (b) sketch map of New Siberian Islands Archipelago.
Modified after Colpron and Nelson (2011).

The New Siberian Islands were extensively studied 30–40 years ago by Kos'ko et al. (1985), when the first geological maps were constructed. The few more recent studies were focused on the geology of the Anzhu Islands, which comprise the largest islands within the archipelago with the most extensive exposures (Meledina, 1999; Kos'ko and Trufanov, 2002; Kuzmichev, 2009; Ershova et al., 2015a,b and references therein). By contrast, comparatively few studies have focused on the small De Long Island group, with many aspects of their geological history still up for debate (Sobolev et al., 2014).

Zhokhov and Vil'kitsky islands are almost entirely covered by Cenozoic basalts and therefore offer a limited insight into the Paleozoic and Mesozoic geology of this part of the archipelago (Silantyev et al., 1991, 2004). By contrast, Paleozoic and Mesozoic strata are exposed on Jeannette, Henrietta and Bennett islands. An in-depth study of these deposits is important for understanding the history of the vast eastern Siberian shelves and, thus, for any plate tectonic reconstructions and paleogeographic inferences for the Arctic realm during the Paleozoic.

Bennett Island is the best studied within the island group, containing exposures of Cambrian–Ordovician sedimentary rocks (mainly carbonates) overlain by Early Cretaceous (Aptian–Albian) basalts (Vol'nov and Sorokov, 1961; Kos'ko et al., 1985; Drachev and Saunders, 2006; Kos'ko et al., 2013; Danukalova et al., 2014). Basic geological mapping was carried out on Henrietta Island during a single field excursion in the 1970s. The stratigraphic relationships between the strata were defined and a broad but debatable "Paleozoic" age was assigned (Vinogradov et al., 1975). Jeannette Island was visited be M.M. Ermolaev in the 1930s and almost no data appear to be available from this trip. The principle aim of this paper is to fill in these critical gaps in geological knowledge and present data and interpretations obtained from two expeditions to the De Long Islands carried out during the summers of 2011 and 2013.

Our primary objectives were to: (1) study the geological structure, (2) provide a description of the sedimentary rocks and determine their depositional environments, (3) study the provenance of the sedimentary succession by means of U/Pb geochronology of detrital zircons, (4) determine the age of the sedimentary successions of Henrietta and Jeannette islands, (5) date the various magmatic rocks that occur on the De Long Islands, and (6) therefore shed light on the paleogeographic history of the De Long Islands and broader Arctic realm.

## 2. Sampling and analytical procedure

### 2.1. U–Pb zircon dating

Detrital zircons of four sedimentary rock samples have been dated using the SHRIMP-II facility at VSEGEI (St. Petersburg), two samples using Cameca IMS 1280 (NORDSIM, Stockholm), four samples in LA-ICP-MS in Washington State University (Apatite to Zircon Inc.) and four at the Geological Survey of Denmark and Greenland (GEUS). Following Gehrels (2012), only analyses with discordance between 30% and -10% were used for the following interpretation. The analytical procedure and data tables are presented in Supplementary 1. U–Pb dating of magmatic rocks was carried out using the SHRIMP-II facility at VSEGEI (St. Petersburg) (six samples) and the Cameca IMS 1280 (NORDSIM, Stockholm) (two samples). $^{207}Pb/^{206}Pb$ ages are reported for >1.0 Ga grains and $^{206}Pb/^{238}U$ ages for ≤1.0 Ga grains.

### 2.2. Ar–Ar dating

The whole-rock fraction >200 μm of sample HL 11-014 was selected for $^{40}Ar/^{39}Ar$ incremental-heating dating performed by Activation

Laboratories Ltd. (Actlabs), Ancaster, Canada. The analytical procedure and data tables are presented in Supplementary 2.

### 2.3. Petrography studies

A total of 20 thin-sections of sedimentary rocks were counted according to the Gazzi–Dickinson method (Gazzi, 1966; Dickinson, 1970; Ingersoll et al., 1984). For each sample, greater than 300 grains were categorized. Data were parameterized for each sample and calculated as: $Q_{total} = Q_{monocrystalline}$ ($Q_m$) + polycrystalline quartz ($Q_p$), Total Feldspar ($F_{total}$), and lithic grains of sedimentary ($L_s$), volcanic ($L_v$) and metamorphic ($L_m$) rocks. All data are listed in Supplementary 3.

### 2.4. Geochemical studies

Twelve analyses of volcanic rocks were performed at the All Russian Geological Research Institute (VSEGEI) in St. Petersburg. Whole-rock major element concentrations were determined by XRF using an ARL 9800 spectrometer, whereas trace and rare earth elements (REE) were determined by an Optima 4300DV emission spectrometer coupled to an ELAN 6100 DRC Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). HL11-014 was analyzed at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany. Major element concentrations were determined by XRF analysis using a PANalytical Axios spectrometer with Rh tube. Trace elements and REE were analyzed by ICP-MS using an Agilent 7500ce instrument equipped with an autosampler (ASX 520, Cetac Technologies). The measured concentrations are listed in Supplementary 4.

## 3. Results

### 3.1. Jeannette Island

Jeannette Island has an area of only 3 km$^2$ with 100 to 350 m high continuous rocky cliffs around its perimeter and a permanent ice cap covering the top of the island. The island was inaccessible for the 2011 expedition and only the southern part of the island could be studied during 2013, due to sea ice and weather conditions (Fig. 2). The cliffs here expose a 435 m thick succession of volcano-sedimentary rocks with subordinate layers of tuffs and volcanic flows, penetrated by mafic dikes and sills (Fig. 2). Volcano-sedimentary rocks generally dip towards the ENE. Similar folds accompanied by cleavage and E-dipping thrusts with displacements few tens of meters are common. Hinges of folds and intersection lineations of cleavage and bedding plunge towards the north–northeast with angles that range from 10 to 30°. Some normal faults have fault planes inclined to the E, while intruding dolerite dikes trend mainly towards the NW.

The volcaniclastic rocks studied on Jeannette Island belong to one unit (unit A of Fig. 2b) that consists of several beds with varying thickness and composition:

Bed 1 is ~125 m thick and consists of fine-grained volcaniclastic turbidites, occasionally interspersed with thin layers of coarse-grained sandstones and grits. Coarse-grained sandstones and grits occasionally

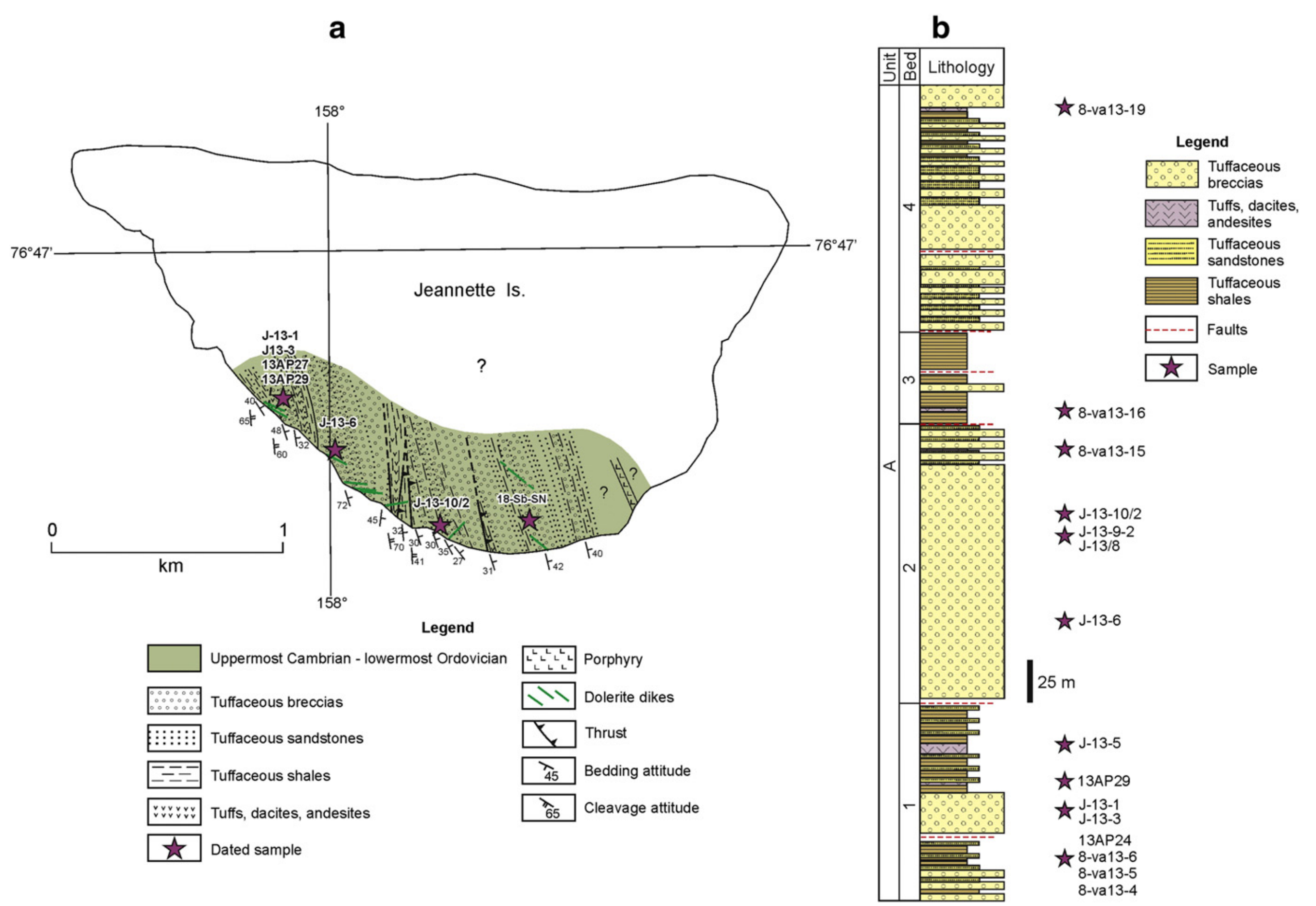


**Fig. 2.** (a) Geological map of Jeannette Island with localities of dated samples; (b) Stratigraphic section of Jeannette Island.

mark the base and fine upward to fine-grained sandstones and siltstones at the top of each individual turbidite sequence. Syn-sedimentary slump folds and convolute bedding occur in the middle part of Bed 1, where a few layers of tuffs and lava flows were also observed.

Bed 2 is >160 m thick and represented by mainly grain-supported tuffaceous breccias with a sandy or silty matrix. The individual pebbles are poorly rounded and sharp-edged, composed of fragments of mainly andesitic volcanic rocks.

Bed 3 is >50 m thick and composed of fine-grained volcaniclastic turbidites and minor tuffaceous breccias. The individual turbidite sequences range in thickness from 5 to 20 cm, typically comprising fine-grained volcaniclastic sandstones at the base, fining upward to siltstone and shale at the top of each individual sequence. Some pebbly to gravelly tuffaceous matrix-supported breccias are interspersed, comprising angular to sub-angular pebbles composed of fragments of volcanic rocks (andesite, dacite and occasionally basaltic andesite).

Bed 4 is >150 m thick and comprises predominantly coarse-grained volcaniclastic turbidites. Pebbly to gravelly breccias with a sandy matrix mark the base of each individual turbidite, gradually fining upward to medium- and coarse-grained sandstones. The uppermost part of each turbidite sequence is capped by sandstones and, rarely, siltstones. The thickness of each graded turbidite sequence ranges from 15 to 35 cm. Few levels of tuffaceous breccias were observed.

Subordinate beds of tuffs and lava flows occur throughout succession. The volcanics are mainly dacite and andesite in composition (Fig. 3).

### 3.1.1. Sandstone petrography and U/Pb dating of detrital zircons

The overall average composition of Jeannette Island sandstones is Q13%, F56%, and L31%; these sandstones are therefore classified as

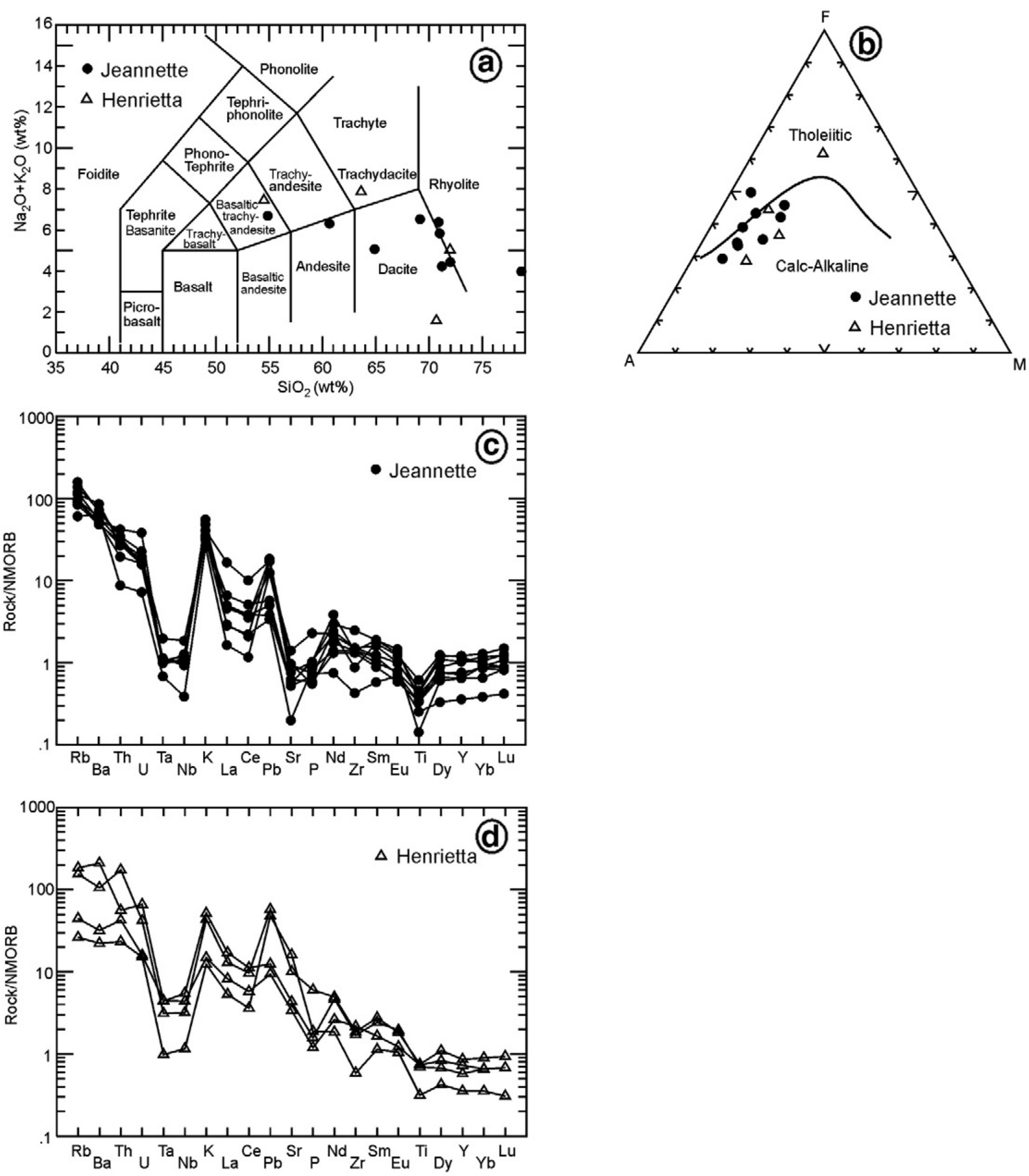


**Fig. 3.** Geochemical diagrams for volcanic rocks of the Jeannette and Henrietta islands: (a) TAS diagram (after Le Maitre et al., 2002); (b) AFM diagram ($A = Na_2O + K_2O$, $F = FeO + Fe_2O_3$, $M = MgO$). The boundary between the tholeiitic and calc-alkaline series is from Kuno (1968); (c) and (d) N-MORB normalized multi-element plots. N-MORB is from Sun and McDonough (1989).

arkosic arenites. Feldspar clasts are the most abundant constituent and are angular or slightly rounded in shape, comprising 45–69% (average 56%) of the framework. Quartz clasts comprise from 11 to 14% of the framework (Fig. 4). Lithic fragments comprise 19–40% of the studied sandstones and consist entirely of medium- and coarse-grained, subrounded, or angular grains of volcanic rocks.

The volcaniclastic rocks of Jeannette Island contain very few zircons. To obtain a sufficient number of zircons for provenance analysis, 4 samples had to be combined (J13-1, J13-3, J13-6, J13/10-2, Fig. 5). Neoproterozoic to early Paleozoic ages dominate within the zircon population. Neoarchean to Mesoproterozoic ages are dispersed and comprise the most significant peak at 1850 Ma and the oldest one at 2850 Ma. Neoproterozoic ages prevail and form three peaks at 595, 620 and 660 Ma. Five ages cluster at 485 Ma and define the maximum age of sedimentation as earliest Ordovician

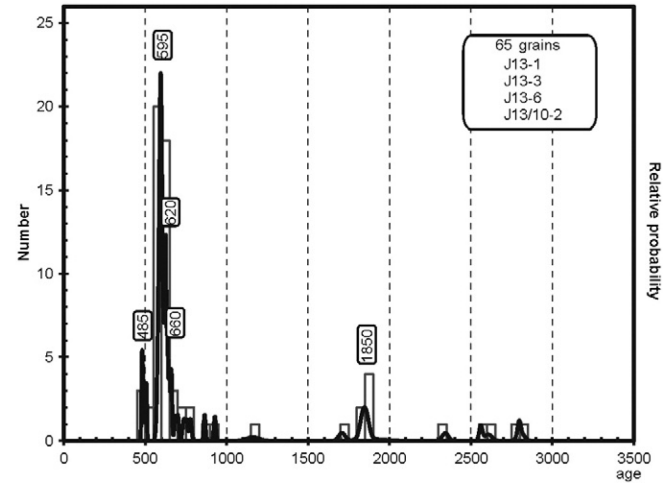


**Fig. 5.** Probability distribution plot of detrital zircon U–Pb ages of samples from Jeannette Island.

### 3.1.2. U/Pb dating of magmatic rocks

Lava flows and tuffs were dated to identify the time of magmatic activity and the age of deposition for the studied succession.

Sample 13AP29 (Fig. 2) is a rhyodacite from a subvolcanic sill (Fig. 6). Zircons are euhedral and clear with well-developed growth zoning. Six grains were analyzed. Two gave Mesoproterozoic ages of c. 1100 Ma, one an age of c. 690 Ma, and the remaining three zircons yielded a concordia age of 483.3 ± 20 Ma; about the same age as the cluster of the youngest detrital zircons.

Sample 18SB-SN (Fig. 2) is a quartz-feldspar porphyry. Eighteen euhedral to sub-rounded zircons were dated. All zircons show crystal zoning, but some of them have cracks. All dated grains yielded Precambrian ages. The three oldest grains are dated to ca. 2600, 1860 and 1100 Ma with the remaining analyses yielding Neoproterozoic ages, whereby ten zircons result in a concordia age of 626.6 ± 3.9 Ma (Fig. 6). The obtained ages are significantly older than the maximum sedimentation age of the underlying volcaniclastic unit, based on the youngest detrital zircon ages from that unit. However, the Neoproterozoic ages are similar to major peaks obtained from the underlying volcaniclastic unit and suggest that those grains were assimilated into the magma as it intruded through this older country rock.

The 13AP27 sample has been collected from a relatively thin sill of trachybasaltic composition. Thirty zircon grains were dated, of which twenty three zircons yielded Precambrian ages. Four grains are latest Mesoproterozoic in age (ca. 1300, 1220, 1110, and 1025 Ma) but most grains are late Neoproterozoic, ranging from 670 to 615 Ma. Seven zircons show Early Cretaceous ages and 4 analyses give a concordia age of 112.1 ± 2.6 Ma (Fig. 6). This mafic sill is possibly co-magmatic with numerous mafic dikes that penetrate the Jeannette Island Paleozoic rocks.

### 3.2. Henrietta Island

Henrietta Island occupies an area of about 15 km$^2$ and is surrounded by 50 to 100 m high continuous rocky cliffs around its perimeter. It comprises two different sedimentary units which were subsequently intruded by mafic dikes and sills (Fig. 7). Thick beds of basalt and andesitic basalt unconformably overlie a deformed sedimentary succession.

The intensity of tectonic deformation varies across the island. The most intense deformation, folding and thrusting towards the WSW, occurs in the southwest. Fold hinges range from gently to steeply plunging and both recumbent and overturned folds are common. Thrusts have often a strike–slip component of displacement, while cleavage is absent. By contrast, in the south, east and north of the island, the strata are monoclinal with gently dipping beds. The succession is intruded by dolerite dikes of NW strike, just as on Jeannette Island.

The composite section of the sedimentary succession comprises two different units (A and B; Fig. 7b).

Unit A (Fig. 7b) is a volcaniclastic sedimentary succession similar to that observed on Jeanette Island, consisting of volcaniclastic turbidites

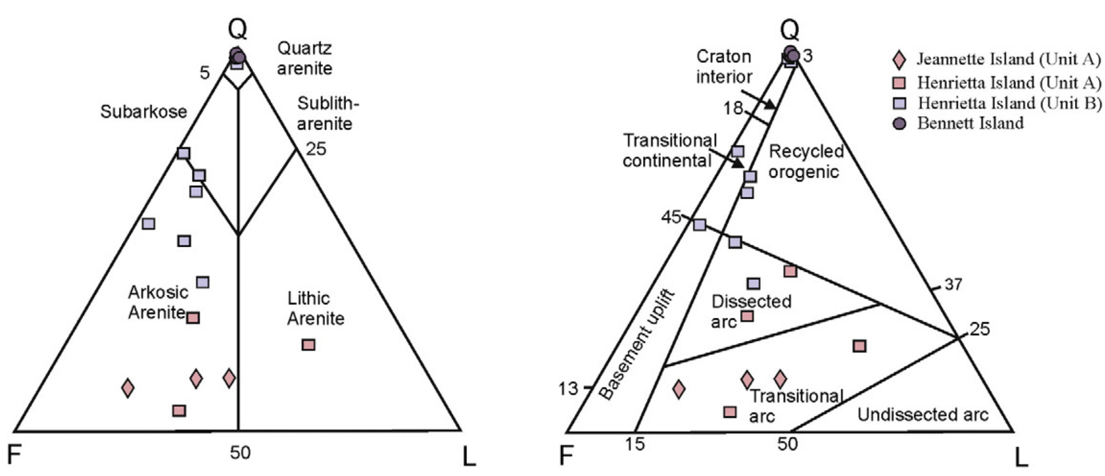


**Fig. 4.** QFL diagrams after Pettijohn et al. (1987) and Dickinson et al. (1983) for the classification and provenance of sediments from Jeannette, Henrietta and Bennett islands. Q = Qm + Qp, where Qm — monocrystalline quartz, Qp — polycrystalline quartz; F — feldspar, L — lithic fragments. For each sample more than 300 grains were counted and categorized.

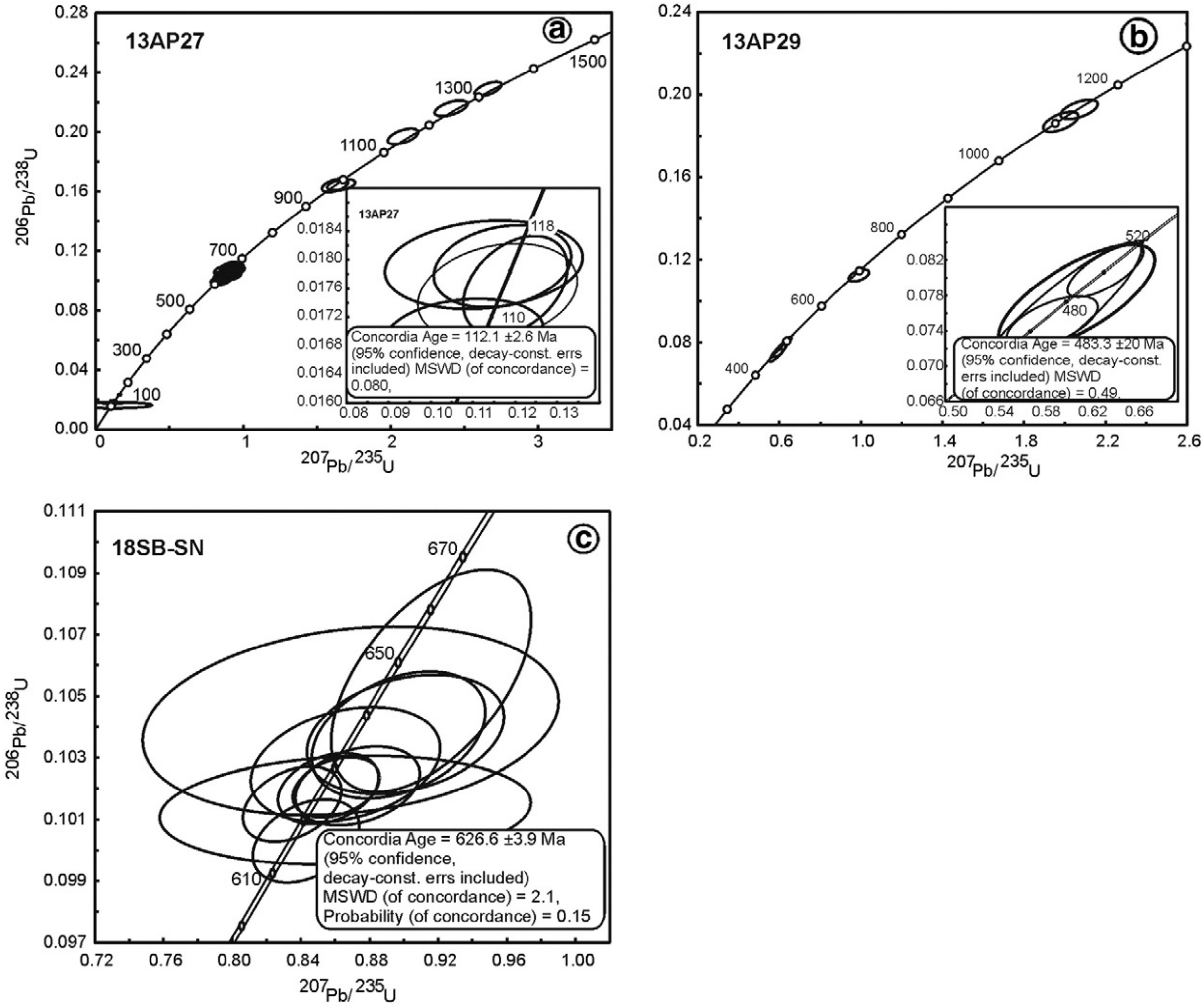


**Fig. 6.** U–Pb zircon dating results of magmatic rocks from Jeannette Island.

with layers of tuffaceous breccias. Subordinate tuff layers and volcanic rocks are mainly dacitic to andesitic in composition (Fig. 3). The volcaniclastic turbidites are mainly fine-grained, displaying normal grading from volcaniclastic siltstones to mudstones at the top. The thickness of individual fine-grained turbidite sequences varies from 3 to 7 cm. Occasional 15–20 cm thick layers of coarse-grained turbidites occur throughout the succession, fining upward from medium-grained tuffaceous sandstones and grits at the base to siltstones. Rare 5–15 cm thick beds of pebbly to gravelly breccias with a sandy matrix were observed at the base of the coarser turbidite sequences, containing pebbles composed of volcanic rocks. Syn-sedimentary slump folds exist in several levels of Unit A, along with several meters of red tuffs. The composite thickness of Unit A is estimated to 150 m.

Unit B. The lower part of the unit (Fig. 7b) is composed of medium- to coarse-grained grayish-brown sandstones and siltstone with beds of polymictic conglomerates that conformably overlies Unit A. Sandstones are planar and parallel-laminated with numerous mud chips. Conglomerates are usually clast-supported but matrix-supported conglomerates are also present. Cobbles and pebbles within the conglomerates range from sub-angular to rounded and are composed of schist, granites, and quartz. Clasts of volcanic rocks comprise less than 40–20% of the total volume. The matrix consists of medium- to coarse-grained lithic sandstone and has the same composition as the sandstones of Unit B. A bed of basaltic andesite was observed in Unit B in the northern part of the island. The thickness of the lower part of Unit B is about 160 m.

The upper part of the succession is 140 m thick and comprises red to pale beige medium- to coarse-grained quartzose sandstone, with beds of quartz conglomerates and subordinate beds of siltstones. Sandstones are parallel and planar-laminated with occasional ripple marks.

### *3.2.1. Sandstone petrography and U/Pb dating of detrital zircons*

Unit A. The overall average composition is Q25%, F39%, and L36% (Fig. 4); these sandstones are therefore arkosic and lithic arenites. Feldspar grains are the most abundant, constituting 28–44% of the framework, and are mostly represented by medium- or coarse-grained angular grains. Quartz clasts constitute 6 to 42% of the framework, displaying a wide range of grain size, and are mostly sub-angular to sub-rounded. Lithic grains constitute 24–54% of the studied sandstones and are mostly represented by medium- or coarse-grained, sub-rounded, rounded or angular grains. The identified grains are exclusively of volcanic origin.

Unit B. The overall average composition is Q67%, F25%, and L8% (Fig. 4). Sandstones are mostly sub-arkose, arkosic arenite and quartz arenite. Quartz clasts are the main component; comprising 39–98% of the rock's framework, with mainly monocrystalline quartz grains. Quartz clasts are of widely varying size and sub-rounded or rounded in shape. Feldspar grains of varying size and sub-angular to rounded shape constitute 1–42% of the studied sandstones. Metamorphic, volcanic and sedimentary lithic fragments were identified. Shale clasts are rare and contribute less than 1–2% of the total lithic fragments. Two

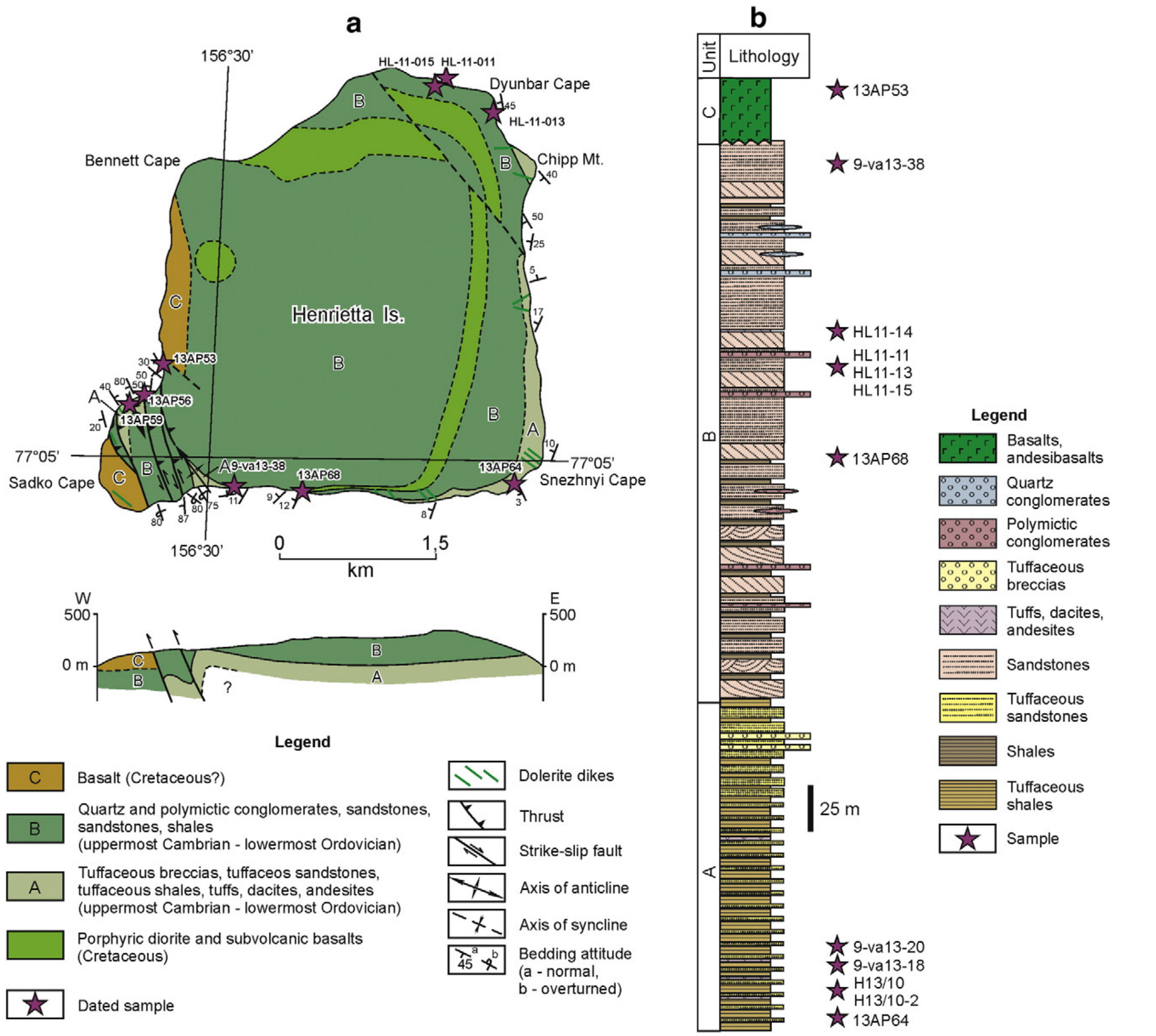


**Fig. 7.** (a) Geological map of Henrietta Island with localities of dated samples; (b) Stratigraphic section of Henrietta Island. Modified after Vinogradov et al., (1975), Kos'ko and Korago (2009).

samples collected in the uppermost bed of Unit B are represented by well sorted quartz arenites with a small percentage of feldspar grains. The quartz clasts are mostly represented by moderately to well-sorted monocrystalline grains of sub-rounded to rounded shape.

Six sandstone samples have been dated to obtain detrital zircon ages.

Unit A. One sample (13AP64; Fig. 7) of volcaniclastic rocks has been dated (Fig. 8), with all dated grains being Precambrian in age. The sample yielded one Archean zircon dated at 3200 Ma, while Paleoproterozoic grains comprise 10% of the zircon population and do not form significant peaks. Mesoproterozoic and Neoproterozoic grains comprise 84% of the total population. Mesoproterozoic zircons have peaks around 1475 and 1120 Ma, while Neoproterozoic zircons form peaks at 975 Ma, 660 Ma, and 565 Ma.

Unit B. Five samples have been dated from Unit B. Four of these samples show a similar distribution of detrital zircons — HL11-011, HL11-013, HL11-015, and 13AP68 (Fig. 7). Three percent of the dated grains are Archean in age and do not group in a peak, while Paleoproterozoic zircons comprise thirteen percent of the total population with most ages concentrated between 1800 and 1600 Ma (Fig. 8). Thirty nine percent of the dated zircons are of Mesoproterozoic age and form multiple peaks between 1560–1450, 1365–1290, and 1220–1000 Ma. Neoproterozoic grains comprise 45% of the population and group around ca. 990, 940, 850, 720, 660, 615, and 590 Ma.

The 9-va13-38 sample (Fig. 7) originated from the uppermost beds of quartzose sandstone in Unit B. It was collected in the southwestern part of the island and shows a significantly different detrital zircon distribution (Fig. 8). The four Paleoproterozoic grains yielded ages between 1764 and 1679 Ma, while the Mesoproterozoic grains comprise 17% of the population, ranging in age from 1350 to 1000 Ma and not forming any significant peaks. Neoproterozoic grains are predominant and comprise 60% of the dated grains, grouping in a major peak at 550 Ma. Twenty percent of the dated zircons are of Paleozoic age, of which 18% are Cambrian and range between 540 and 520 Ma and two are Ordovician and dated at 426 and 484 Ma.

### 3.2.2. U/Pb dating of magmatic rocks

Samples from sills have been dated to determine a minimum age of deposition.

Sample 13AP53 (Fig. 7) consists of basaltic andesite sampled from a 50 m thick sill. The obtained zircon ages vary from Archean to

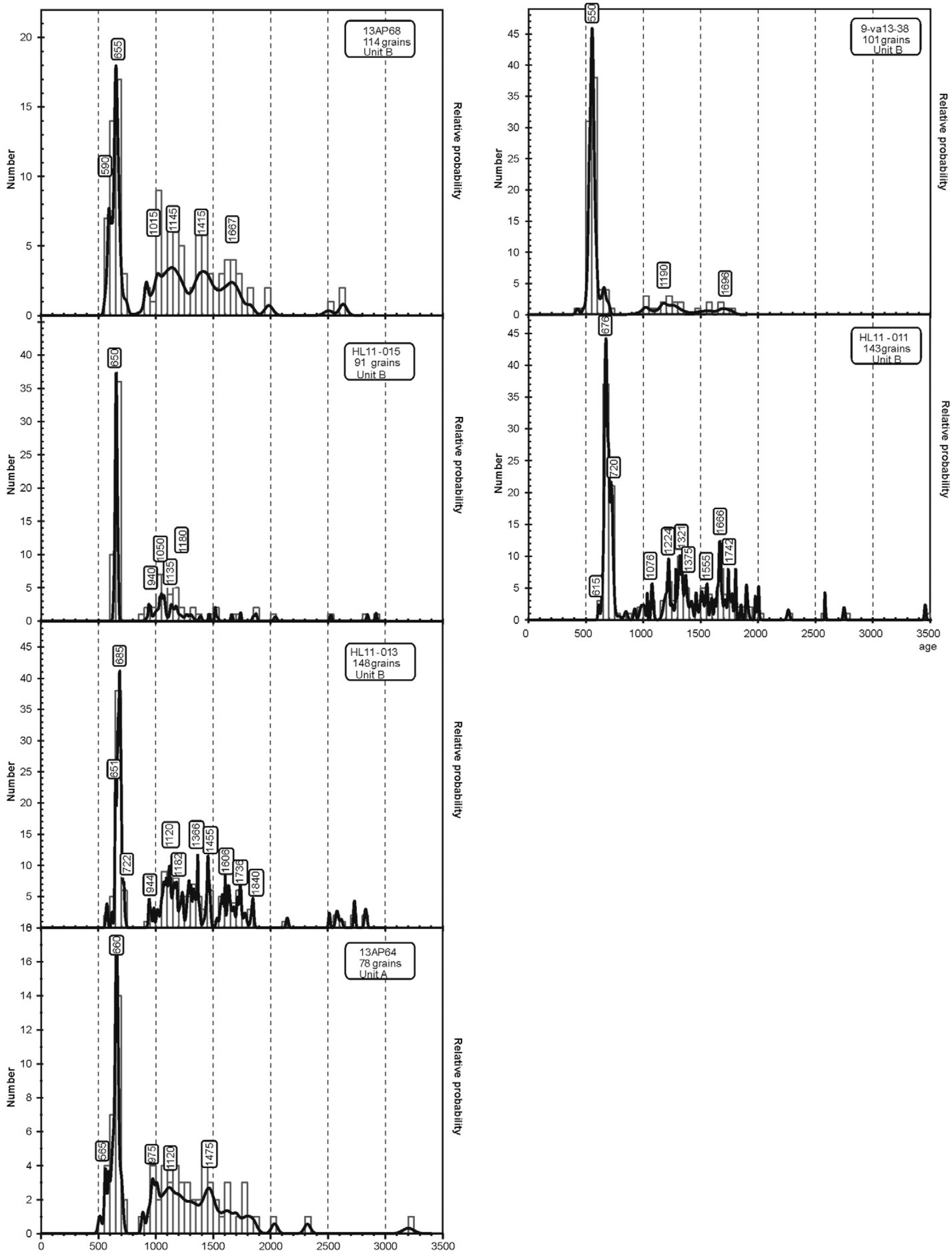


**Fig. 8.** Probability distribution plot of zircon U–Pb ages of samples from Henrietta Island.

latest Neoproterozoic, implying that these grains were assimilated from the surrounding country rock during intrusion of the magma (Fig. 9).

Sample 13AP56 (Fig. 7) is a dolerite collected from a dike which crosscuts Unit B and therefore must be younger in age. Fourteen zircon grains were dated in total, yielding ages ranging from Mesoproterozoic to Cambrian (Fig. 9). Two Mesoproterozoic age peaks occur at c. 1410 and 1320 Ma, four grains yield Neoproterozoic age peaks from 950 to 570 Ma, but the majority of dated grains are of Early–Middle Cambrian age. This broad range of ages is similar to the main peaks obtained in the detrital zircon ages of the host rock. Concordia ages of 563.6 ± 4.3 Ma and 535 ± 4 Ma are within the range of ages of the granitic xenoliths from Zhokhov Island (see below), which suggests assimilation of zircons also from granitic basement

Sample 13AP59 (Fig. 7) is a trachybasalt that was collected from a 20 m thick sill. Six zircon grains were dated (Fig. 9), half of which yielded Precambrian ages and the other half gave a concordia age of 135.9 ± 2.8 Ma, confirming that Early Cretaceous magmatic rocks are also present on Henrietta Island.

Zircons were not found in basaltic trachyandesite sample HL11-014. Ar–Ar dating of the whole-rock fraction >200 μm yielded a plateau age of 419.2 ± 3.7 Ma (1 sigma; Fig. 9) for five intermediate to high temperature degassing steps including 64.4% of the released $^{39}Ar$. The plateau age is similar to the total gas age of 417.7 ± 3.7 Ma (1 sigma). The

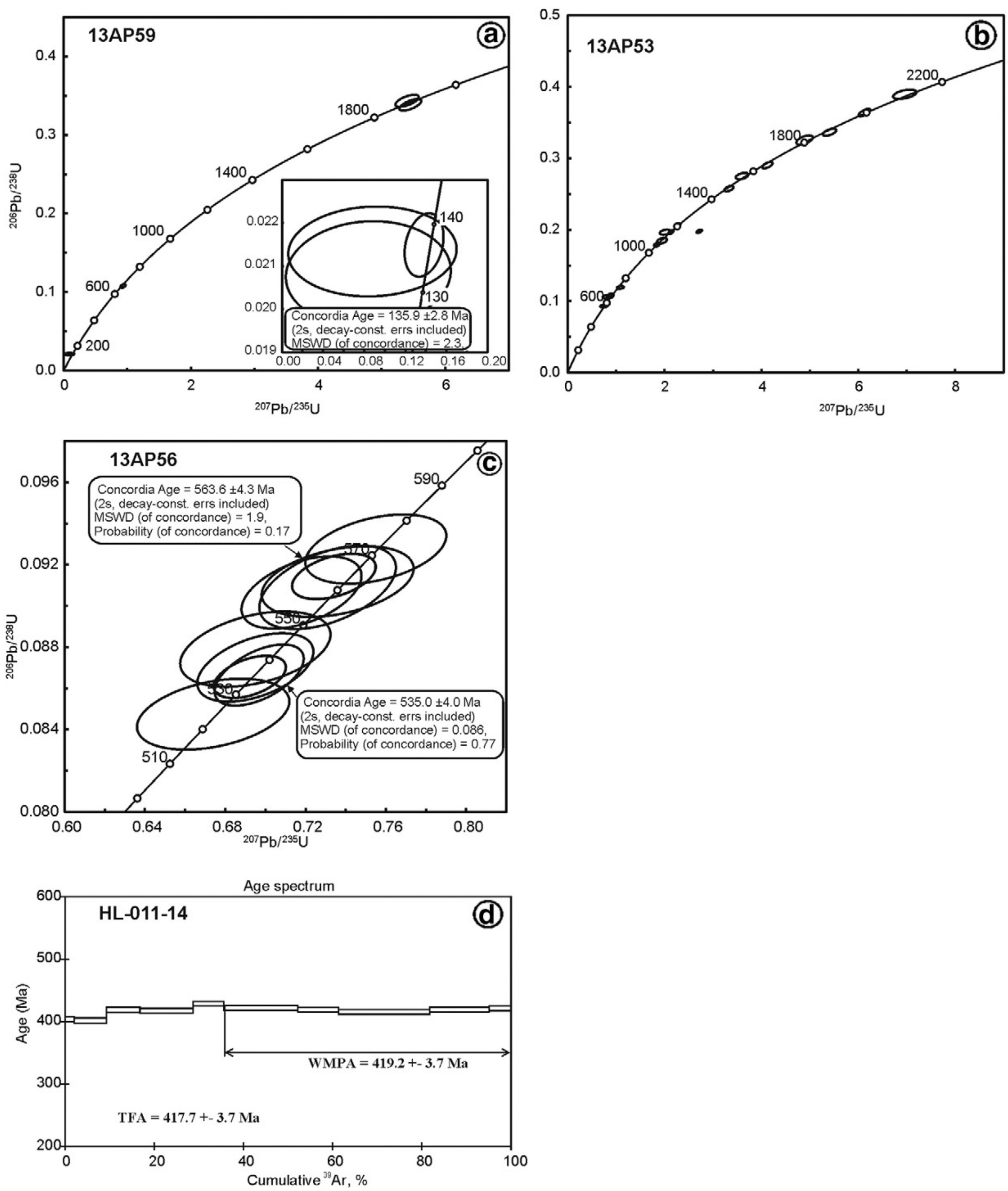


**Fig. 9.** (a–c) U–Pb zircon dating results of magmatic rocks from Henrietta Island, (d) — Ar–Ar dating results of magmatic rock from Henrietta Island.

inverse isochron calculation yields evidence for excess argon (initial $^{40}Ar/^{36}Ar$ of 445 ± 40; 1 sigma).

### 3.3. Bennett Island

Bennett Island (Fig. 10a) is the largest island in the De Long archipelago, about 30 km in length and up to 14 km wide, and is composed of a weakly deformed Lower Paleozoic sedimentary succession. In the southern part of the island, the Cambrian–Ordovician rocks are deformed into a wide open anticlinal fold. The hinge of this fold is subhorizontal and trends to the north, cleavage is absent. Some small east-trending reverse faults occur. The Lower Paleozoic strata is unconformably overlain by Early Cretaceous sandstones and basalts (Fig. 10b) that yielded Aptian–Albian K–Ar ages of 119–112 ± 5 Ma (Drachev, 1989) as well as 124 ± 6, 110 ± 5, 109 ± 5 and 106 ± 4 Ma (Fedorov et al., 2005).

The Lower to Middle Cambrian deposits consist of a 400 m thick succession of alternating sandstones and siltstones in the lower part and mostly carbonate rocks in the upper part. According to Danukalova et al. (2014), the lower mainly siliciclastic part of the Lower–Middle Cambrian succession is characterized by numerous hummocky cross-stratified beds with washover channels. The upper part of the succession comprises alternating marls, limestones and limy shales with subordinate thin beds of siltstones and fine-grained sandstones. The main characteristic of the calcareous part of the succession is the presence of amalgamated hummocky cross-stratified beds with numerous hardground surfaces. The Upper Cambrian to lowermost Ordovician rocks comprise more than 100 m of black shales with occasional beds of siltstones and fine-grained sandstones. The shales are parallel-laminated while siltstones and sandstones form relatively thin hummocky cross-stratified beds. The 600–800 m thick Lower to Middle Ordovician succession is represented by carbonate rocks in the lower part, passing upwards into siliciclastic deposits (Kos'ko et al., 1985). The lower part comprises alternating hummocky and swaley cross-stratified limy shale, marls and limestones with rare hardground surfaces. The upper siliciclastic part is represented by alternating dark gray shales with subordinate beds of fine- to medium-grained quartz sandstones.

#### 3.3.1. Sandstone petrography and U/Pb dating of detrital zircons

The Middle Cambrian and Lower Ordovician sandstones are similar in composition and are described together here. The overall average composition is Q 99.5%, F 0.5%, L 0% (Fig. 4), classifying these sandstones as quartz arenites. Quartz grains are the most abundant constituent and are mainly represented by very fine-grained rounded and sub-rounded monocrystalline grains.

Detrital zircon signatures have been obtained from three samples. Sample 13AP71 (Fig. 10) is Cambrian in age (Fig. 11). Paleoproterozoic and Archean grains do not form significant peaks and together comprise 20% of the dated grains. The Mesoproterozoic grains comprise 49% of the

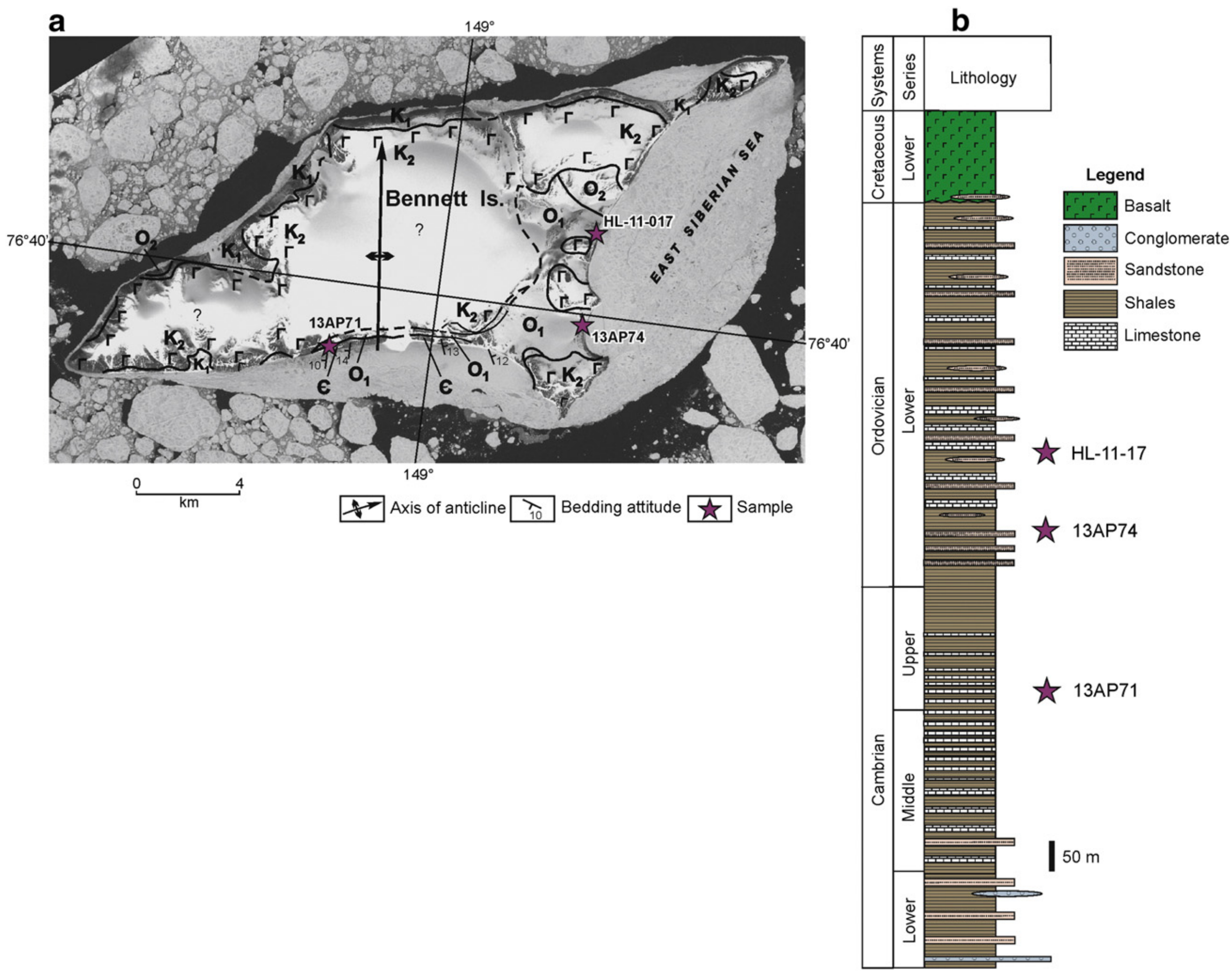


**Fig. 10.** (a) Landsat image of Bennett Island with localities of dated samples. (Є — Cambrian, O1 — Lower Ordovician, O2 — Middle Ordovician, K2 — Upper Cretaceous); b — stratigraphic section of Bennett Island (after Vinogradov et al, 1975; Danukalova et al., 2014).

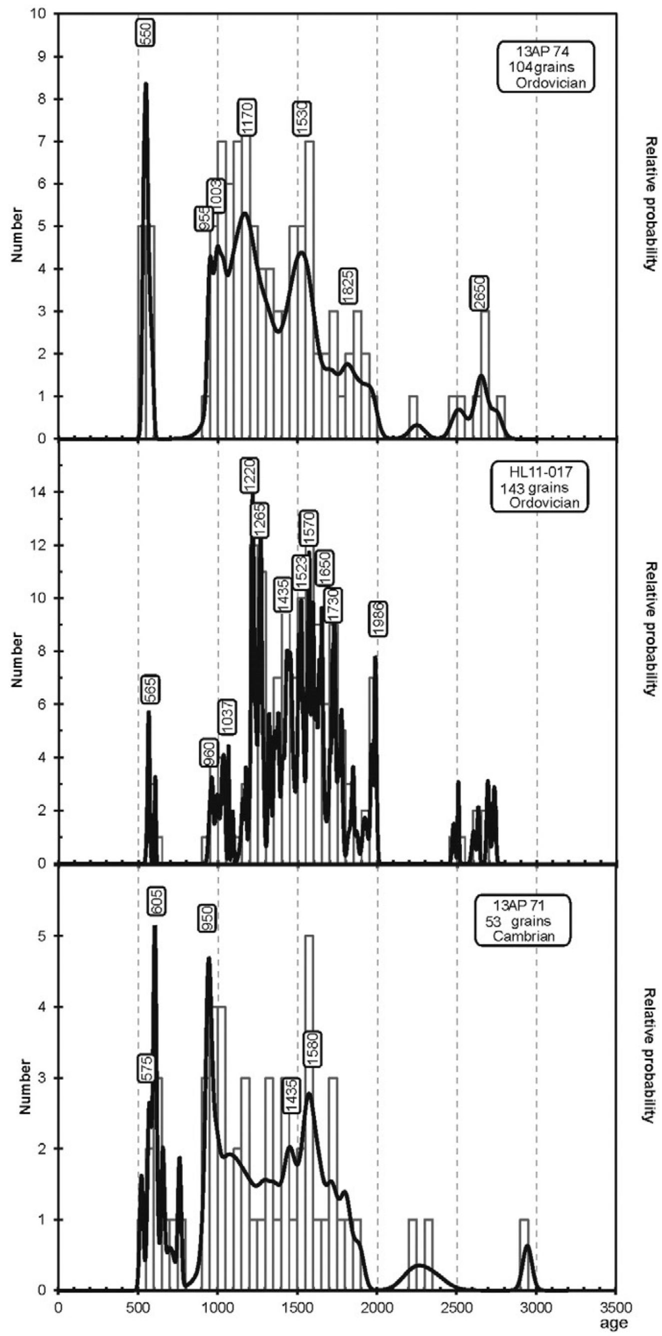


**Fig. 11.** Probability distribution plot of detrital zircon U–Pb ages of studied samples from Bennett Island.

dated grains, forming two peaks at 1580 and 1435 Ma. 28% of the dated grains are Neoproterozoic in age, forming major peaks at 950 and 605 Ma with a subordinate peak at 575 Ma. Only one grain yielded a Cambrian age of 522 Ma.

The detrital zircon signatures of two samples (13AP74, HL-11-017; Figs. 10 & 11) from the Ordovician rocks are quite similar. A few Archean grains have ages between 2800 and 2500 Ma (Fig. 11), with a peak at 2655 Ma in 13AP74. Paleoproterozoic grains comprise 13% of the population and are grouped into three peaks at 1990, 1830 and 1730 Ma. Mesoproterozoic grains are predominant (60%) and form several peaks, with ages between 1700–1400 Ma and 1300–1000 Ma. Neoproterozoic grains comprise 10% of the population and besides the broad assemblage of Mesoproterozoic ages that extends into the Early Neoproterozoic (to c. 900 Ma), a latest Neoproterozoic peak at ca. 560–550 Ma is present.

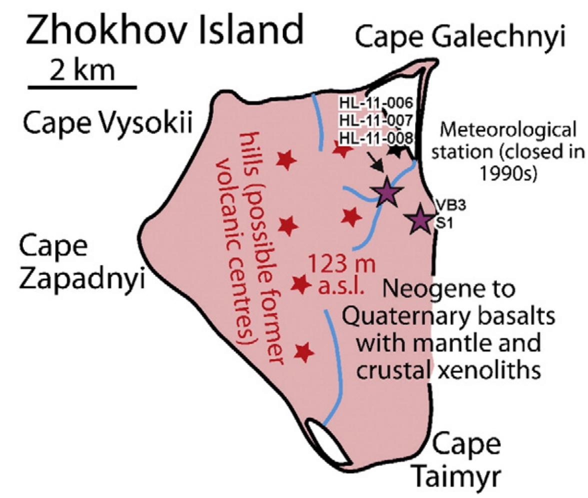


**Fig. 12.** Simplified map of Zhokhov Island with localities of dated samples.

Only one Cambrian grain has been dated in both samples and yielded an age of 532 Ma.

### 3.4. Zhokhov Island

Zhokhov Island is an eroded late Cenozoic stratovolcano (Fig. 12), with sea cliffs containing exposures of alternating flows of massive and blister lava, agglomerate and tuff, variable in texture, structure, porosity, and color. Massive columnar conduit fill basalts outcrop on the top of the hills, with the basalts mostly of picrite–olivine type and layers of volcanic ash containing large volcanic bombs (Kos'ko and Trufanov, 2002). The Ar–Ar age of basalts from Zhokhov Island is 1.20 ± 0.19 Ma (Layer et al., 1992). Xenoliths of different composition, such as sandstones, carbonates, granites, syenites, and dolerites, frequently occur within the various volcanic rocks that constitute the Zhokhov volcano. Makeev et al. (1991) demonstrated that the carbonate xenoliths are Carboniferous limestone. K–Ar dating of the dolerite yielded ages ranging from 152 to 99 Ma (Gramberg et al., 2004), while the spinel lherzolite yielded a Sm–Nd age of 1110 ± 57 Ma (Silantyev et al., 2004).

Detrital zircons from an in-situ sandstone xenolith have been dated (HL11-08; Fig. 13). Paleoproterozoic and Archean grains contribute around 10% of the ages and do not form significant peaks, while

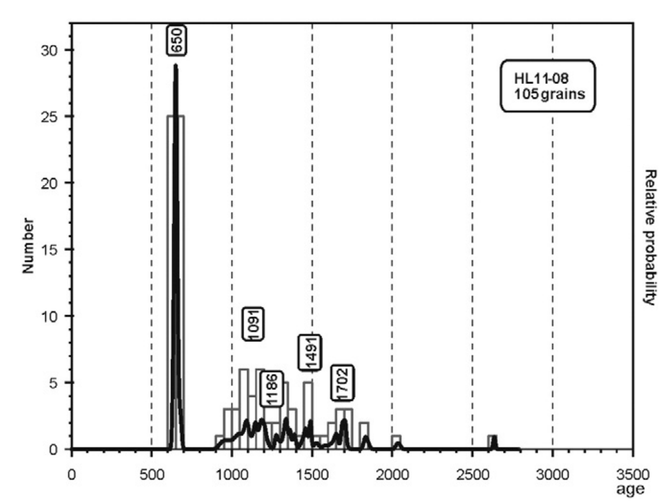


**Fig. 13.** Probability distribution plot of detrital zircon U–Pb ages of sedimentary xenoliths from Zhokhov Island.

Mesoproterozoic grains are mostly between 1350 and 1050 Ma in age. Neoproterozoic ages are predominant and comprise 58% of the zircon age population, with a significant peak at 650 Ma.

Korago et al. (2014) determined the crystallization ages of two felsic xenoliths by U–Pb dating on zircons to 568 ± 3.7 Ma and 602 ± 2 Ma. Our study of granite xenoliths shows that HL11-009 and HL11-010 (Fig. 14) yielded concordia ages of 533.1 ± 1.2 Ma and 578.1 ± 1.5 Ma, respectively. The S1 sample (Fig. 14) shows two concordant zircon populations at 663 ± 7 and 638 ± 5 Ma, possibly representing the ages of crystallization and metamorphism.

A single basalt sample (VB 3) (Fig. 14) yielded a broad range of zircon ages, from 1931 to 12.5 Ma. Paleozoic grains are predominant but a few Precambrian grains occur. These zircons are older than the age of basalts and were assimilated into the magma from the surrounding country rocks, as it ascended to the surface.

## 4. Discussion

### 4.1. Age of basement

No outcrops of basement rocks are known in the whole New Siberian Islands archipelago. The age of the basement beneath the De Long Islands can be estimated by dating assimilated material in the younger volcanic rocks, i.e. zircon xenocrysts from mafic sills and dikes or igneous xenoliths from the late Cenozoic stratovolcano on Zhokhov Island. Granite and granite–gneiss xenoliths from Zhokhov Island yield zircon ages between 670 and 535 Ma, suggesting the presence of late Neoproterozoic crystalline basement below the sedimentary sequence, although rocks of such age are not exposed anywhere on the archipelago. The assimilated zircons from sills and dikes on Henrietta and Jeannette islands show a broad range of ages from the Archean to the Neoproterozoic, with late Neoproterozoic ages of 650–560 Ma dominating. Zircons of such an age could be captured from both the crystalline basement and the overlying sedimentary succession. However, the combined data from xenocrysts and xenoliths suggests a strong late Neoproterozoic age component in the basement beneath the De Long Islands.

### 4.2. Depositional environments

The sedimentary succession of Jeannette Island comprises both fine- and coarse-grained volcaniclastic turbidites with thick beds of volcaniclastic breccias. The characteristics of these deposits suggests that they were derived from nearby explosive sub-aerial volcanism, which generated ash fallout and pyroclastic rock discharge to the sea, i.e. they are primary volcaniclastic turbidites derived from pyroclastic material that was directly transported to the sea. Alternatively, the material could have been deposited in shallow water environments and then reworked by secondary volcaniclastic turbidites into the deep sea environment (Carey and Schneider, 2011). However, the presence of thick breccias is evidence against a long transportation distance and suggests deposition of these turbidites close to the eruptive centers,

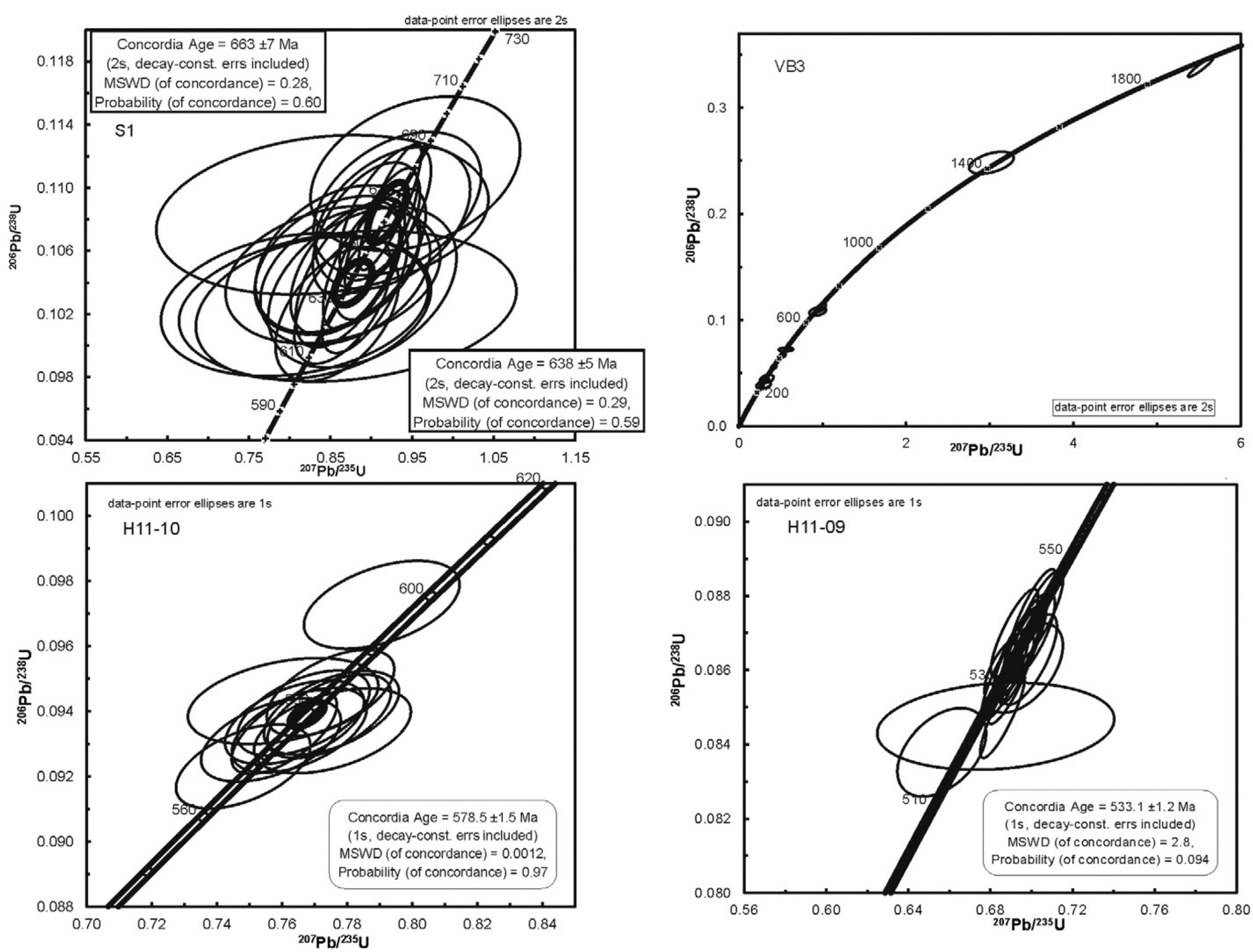


**Fig. 14.** U–Pb zircon dating results of magmatic xenoliths from Zhokhov Island.

thus favoring the primary volcaniclastic turbidite model. The occurrence of slump-folded units indicates the presence of steep slopes.

Volcaniclastic turbidites can originate in a variety of tectonic settings, including mid-ocean ridges, oceanic seamounts, island arcs and continental active margins. Seamounts and oceanic ridges can be discounted as these features are rarely preserved in the geological record and mainly produce mafic effusive volcanics. The volcanic clasts are mainly andesitic and dacitic in composition within the volcaniclastic succession of Jeannette Island, suggesting that they formed in an island arc or continental arc.

The succession of Henrietta Island comprises two contrasting units. The volcaniclastic turbidites with occasional thin beds of breccia in Unit A are more fine-grained than those observed on Jeannette Island, suggesting that they were deposited further from the volcanic source. Unit B is represented by various sandstones with subordinate beds of polymict and quartz conglomerates, containing sedimentary structures and facies indicative of deposition in deltaic to shallow marine environments. The shift in depositional environments is interpreted to represent the termination of volcanism, probably coinciding with some kind of tectonic activity that is reflected in the geological record by the influx of more evolved sediments. Granitic and metamorphic pebbles are further evidence for the erosion of exhumed basement rocks in close proximity to the sedimentary basin. The sedimentary environment and lithologies suggest that Henrietta Island was also part of an island arc or continental arc during the Early Paleozoic, but at a more distal location to the eruptive centers than Jeannette Island.

The sedimentary facies of the Lower to Middle Cambrian deposits of Bennett Island are clearly indicative of deposition in a shallow marine shelf environment (Danukalova et al., 2014). The key features of the studied succession are numerous beds with hummocky and swaley cross-stratification, which is usually formed by storm-induced currents above storm wave base, at water depths typically ranging from 20 to 200 m (Nichols, 2009). These structures are destroyed in deposits above fair-weather wave base (c. 20 m) due to constant reworking of the sediments by waves. Siltstone and mudstone layers that separate the tempestite beds were deposited much more slowly during quiescent periods between discrete storm events. The Upper Cambrian to lowermost Ordovician black shales contain only a few hummocky cross-stratified beds, suggesting a deepening of the basin to below storm weather wave base during this time, achieved by a rise in eustatic sea level, tectonic activity resulting in a subsidence phase within the basin, or a combination of the two. The sedimentary facies of the Lower to Middle Ordovician succession suggest a return to deposition in a storm-dominated shelf environment. The Lower Paleozoic succession of Bennett Island is therefore represented mainly by tempestites deposited in a relatively shallow marine basin.

Petrographic studies on a QFL discrimination diagram (Dickinson et al., 1983; Pettijohn et al., 1987) show that the samples from Jeannette and Henrietta islands record a trend from transitional arc to craton interior provenance, i.e. from Jeannette Island and Henrietta Island's Unit A to the youngest samples in Henrietta Island's Unit B (Fig. 4). The presence of numerous volcanic fragments suggests that the clastics were transported over a short distance from source to sink and are likely to have been derived locally. This notion is further supported by the presence of thick volcaniclastic breccias, tuff layers, and volcanic glass in the sandstone matrix, suggestive of deposition in close proximity to the eruption centers. The youngest detrital zircons from Jeannette and Henrietta islands as well as the rhyodacite from Jeannette Island (sample 13AP29) suggest a latest Cambrian to earliest Ordovician age for the volcaniclastic succession, and volcanism therefore appears to have been active across the De Long Island area during this time.

In the upper part of the volcaniclastic succession (Unit B), deposition of coarser grained clastic sediments in a deltaic to shallow marine environment begins to dominate. The petrographic analyses of sandstones from Unit B reveal a decreasing proportion of volcanic clasts up-section, and they cluster in the dissected arc, recycled orogen and transitional continental provenance fields on the QFL discrimination diagram (Fig. 4). Granite and schist pebbles occur throughout Unit B, while volcanic clasts are subordinate, once again suggesting that denudation of continental crust was taking place in close proximity to this area. Andesitic and dacitic volcanism is typical for mature continental margin arcs, where continental crust (of more felsic composition) can be assimilated into the magma as it rises through the crust towards the surface volcano and alter its primary mafic composition, while oceanic island arc volcanics tend to be more mafic in composition (Gill, 2010, and references therein). The geochemical analyses of Jeannette and Henrietta islands' volcanic rocks (Fig. 3) confirms this interpretation. The trend in the AFM diagram suggests that the rocks belong to the calc-alkaline series, the low abundance of Ta, Nb, Zr and the HREEs in the MORB-normalized multielement spider plots are typical for subduction-related magmatism (Gill, 2010). Due to the composition of the volcanic deposits and evidence for exhumed continental crust in close proximity to this area, we conclude that Jeannette and Henrietta islands represent a fragment of an island arc or continental arc that was active in the latest Cambrian and persisted at least into the Early Ordovician.

Sandstones of the Cambrian–Ordovician succession of Bennett Island are mainly very mature quartz arenites that plot in the craton interior provenance field of the QFL diagram, suggesting a longer sediment transport distance from source to sink and/or significant sediment reworking. The detrital zircon age distribution shows a predominance of Mesoproterozoic and Neoproterozoic zircons, with only a few zircons yielding ages close to the succession's stratigraphic age (Early Paleozoic). Therefore, the clastic Cambrian–Ordovician succession of Bennett Island is interpreted to be of continental origin with no or very subordinate volcanic activity.

The coeval Early Paleozoic strata on Bennett Island are therefore very interesting, as they would suggest that very contrasting depositional environments occurred across the De Long Islands during the Early Paleozoic, ranging from shallow shelf marine (Bennett Island) to active continental margin (Jeannette and Henrietta islands) over a relatively short distance. We therefore suggest that while a continental margin volcanic arc occupied the positions of present-day Henrietta and Jeannette islands, neighboring Bennett Island was located on the craton side of a back-arc basin and was therefore relatively isolated from the volcanic output (Fig. 15).

### 4.3. Sediment provenance

There is a striking similarity in the age distribution of detrital zircons from the Lower Paleozoic successions of Henrietta, Bennett and Jeannette islands. This is also true for the zircon ages from the sandstone xenolith of Zhokhov Island and the zircon xenocrysts in the diverse

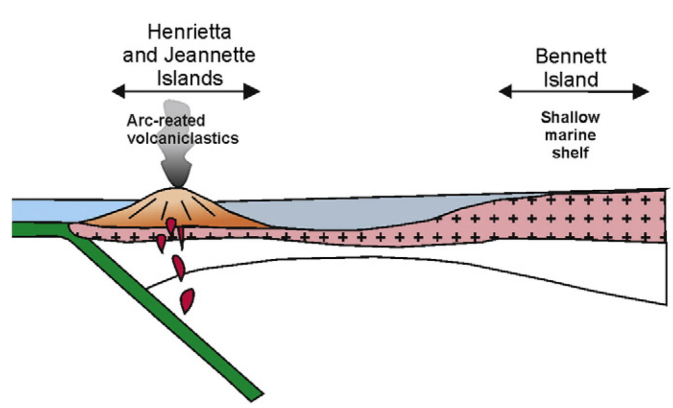


**Fig. 15.** Tectonic model of the De Long Islands in the Early Paleozoic.

analyzed magmatic rocks. The Archean ages that mainly group around 2.7 Ga are not conclusive for a source area as such ages are known from cratons around the Arctic and also occur in other Paleozoic sediments across the Arctic region, e.g. on Svalbard (Pettersson et al., 2010) and Greenland (Strachan et al., 1995). These Archean zircon ages are more abundant, though still fairly subordinate, in the Silurian to Devonian strata of Novaya Zemlya (Fig. 1) and in the Lower Paleozoic strata of Severnaya Zemlya (Lorenz et al., 2008, 2013), i.e. the "closest" islands to the west of the New Siberian Islands. Detrital zircon ages from Henrietta and Bennett islands display a broad assemblage from 2.0 to 0.92 Ga (0.95 Ga on Henrietta), which corresponds to the long time span of basement consolidation in Fennoscandia and Greenland (i.e. Baltica and [eastern] Laurentia; Lahtinen et al., 2008), culminating in the Grenvillian and Sveconorwegian orogenies and persisting until the earliest Neoproterozoic. Latest Paleoproterozoic to earliest Mesoproterozoic ages are a component in the early evolution of the Grenville Province (McLelland et al., 2010), and fit well with the ages of numerous Mesoproterozoic to latest Paleoproterozoic terranes reported from the Sveconorwegian Orogen (Bingen et al., 2008). Latest Mesoproterozoic to earliest Neoproterozoic ages could be related to orogenic episodes in the Grenville–Sveconorwegian Orogeny (Bingen et al., 2008; Rivers, 2008). Recently, it has been suggested that the Grenville–Sveconorwegian Orogen extended northwards from its type areas via the North Atlantic margins of Europe and Greenland into the high Arctic (Lorenz et al., 2012, 2013). Earliest Neoproterozoic basement (granites and gneisses) is exposed on Svalbard (0.96–0.92 Ma; Gee et al., 1995; Johansson et al., 2005; Majka et al., 2014) and East Greenland (0.95–0.92 Ma; Kalsbeek et al., 2000; Watt and Thrane, 2001). These ages fit well with the youngest observed detrital zircon ages of the 2.0 to 0.9 Ga population from the De Long Islands.

After a gap at around 900–700 Ma in the age distribution, the next significant peaks in the relative probability plot occur in the late Neoproterozoic. The younger late Neoproterozioc ages, 620–590 Ma on Jeannette, 580–550 Ma on Henrietta (subordinate), and 610–560 Ma on Bennett, are typical for Timanian basement along the Baltican margin. Gee et al. (2000) reported 620 Ma and 560–550 Ma ages from granites in drill holes that penetrated basement beneath the sedimentary cover of the Pechora Basin. Based on the age of ophiolites (c. 670 Ma; Khain et al., 2003), age of metamorphism (c. 630 Ma, Gee et al., 2007) and broad range of late Neoproterozoic granite ages from the basement of the Timan–Pechora region (c.f. Kuznetsov et al., 2007), Timanian basement ages can be defined as c. 630–550 Ma. Similar zircon age populations are also prominent in the Lower Paleozoic deposits of Novaya Zemlya and Severnaya Zemlya (Lorenz et al., 2008, 2013), in the metamorphic Nome Complex of the Arctic Alaska Terrane (Seward Peninsula; Till et al., 2010) and were reported from the Alexander Terrane in the North American Cordillera (Gehrels, 1990; Beranek et al., 2013).

The older late Neoproterozoic ages, c. 660 Ma on Jeannette (subordinate) and 670–650 Ma on Henrietta (dominating), with some ages around 720 Ma, are older than Timanian basement and also occur in the Lower Paleozoic sediments of Novaya Zemlya and Severnaya Zemlya (Lorenz et al., 2008, 2013), however are much more subordinate there. They are prominent in detrital zircons from the Nome Complex (Seward Peninsula, Arctic Alaska; Till et al., 2010) and in the Alexander Terrane (Beranek et al., 2013), but it is much more difficult to tie them to a particular provenance. Zircon ages of c. 700 Ma are unknown from the Timanides and Baltica. Such ages could fit well with the formation of active continental margins, rifting and development of volcanic arcs around the Siberian Craton (e.g. Yenisey Ridge, Taimyr; Vernikovsky et al., 2004), however Siberia cannot be considered as a provenance for the distinct Archean–earliest Neoproterozoic age peaks described above, because of its significantly different tectonic history. The age of Archean terranes ranges from 3100 to 2500 Ma and the age of Paleoproterozoic terranes from 2500 to 2000 Ma, while the age of terrane amalgamation to form the Siberian Craton has been dated at 2000–1800 Ma (Rozen, 2003; Smelov and Timofeev, 2007, and references therein). The occurrence of Mesoproterozoic rocks is very limited, Neoproterozoic magmatic rocks have only been reported from its margins (Vernikovsky et al., 2004), and Siberia was not affected by the Grenville–Sveconorwegian and Timanian orogenies (Rozen, 2003). The detrital zircon age distribution in the Precambrian to Paleozoic sedimentary strata is also significantly different from that of the De Long Islands. Neoproterozoic detrital zircon ages from the Paleozoic sedimentary strata of northern Siberia have a broader age distribution in the Neoproterozoic, with prominent peaks at 850–800, 750–700 and 650–600 Ma (Ershova et al., 2013; Prokopiev et al., 2013; Khudoley et al., 2015).

A possible explanation for the presence of c. 700 Ma detrital zircons in a Baltican provenance is that one or several volcanic arcs, formed in connection with the late Neoproterozoic development of Siberia, were accreted to the Baltican margin during the Timanian orogeny and subsequently exhumed. Examples of such basement might be preserved on Wrangel Island (Wrangel Complex) with U–Pb crystallization ages of 700–620 Ma (Luchitskaya et al., 2014) and the basement of the Seward Peninsula (870–540 Ma; Amato et al., 2009), both part of the Arctic Alaska–Chukotka Terrane. Also the older xenoliths (670 Ma) from Zhokhov Island are pre-Timanian.

## 5. Paleogeographic restoration

At least four fundamentally different models exist for the tectonic position of the New Siberian Islands during the Paleozoic. The first model, presented by Gramberg et al. (1986), Kuzmichev (2009) and Danukalova et al. (2014), considers the New Siberian Islands to represent the distal north-eastern (in present co-ordinates) passive margin of the Siberian Craton. The Siberian-affinity model is mainly based on the similarity between the faunas of Bennett Island and Siberia. However, evidence for a mixture between Siberian and other faunas in the Early Paleozoic is not uncommon. Lieberman (1997) showed similarities between Laurentian and Siberian Early Cambrian trilobite faunas. Álvaro et al. (2013) reported that the Siberian trilobite fauna is a mosaic of biogeographical units throughout the Cambrian. The younger Ordovician and Silurian fossils show many similarities between Siberian, Laurentian and Baltican faunal assemblages. Antoshkina and Soja (2006) indicated migration of Silurian reef biota between Alaska, Baltica and Siberia. Similarity among the Ordovician bryozoan of Severnaya Zemlya, North America and Estonia was reported by Nekhorosheva (2002). The Ordovician conodont fauna from Alaska is a distinctive mixture of Laurentian and Siberian–Alaskan endemic forms (Dumoulin et al., 2014). And the Early Paleozoic succession of Severnaya Zemlya suggests a connection with North Greenland and the Baltic palaeobasin (Männik et al., 2009). Analysis of the distribution of Ordovician rhynchonelliform brachiopods across the world reveals that Siberia and Laurentia represented the same biogeographic province (Harper et al., 2013). To sum it up, the Early Palaeozoic faunas do not appear to provide conclusive evidence for paleogeographic restorations.

The second model, presented by Zonenshain et al. (1990), considered the New Siberian Islands as part of a large, discrete paleocontinent called "Arctida", which is assumed to include much of the basement beneath the Russian Arctic shelves. This model was based on similarities in the geological record and structural styles of nowadays separated Arctic regions. Some ideas proposed by Zonenshain et al. (1990) have not lost its relevance, like the non-Siberian affinity of the New Siberian Islands and the Severnaya Zemlya archipelago. However, geological similarities and a non-Siberian affinity is interpreted and explained differently in this paper, without reference to a past continent.

The third model is based on paleomagnetic data by Metelkin et al. (2014, 2015) and considers the New Siberian Islands to represent a small terrane located along the eastern margin of Siberia (present-days coordinates) but separated from it during the Neoproterozoic and Paleozoic. This model makes it difficult to explain the deposition

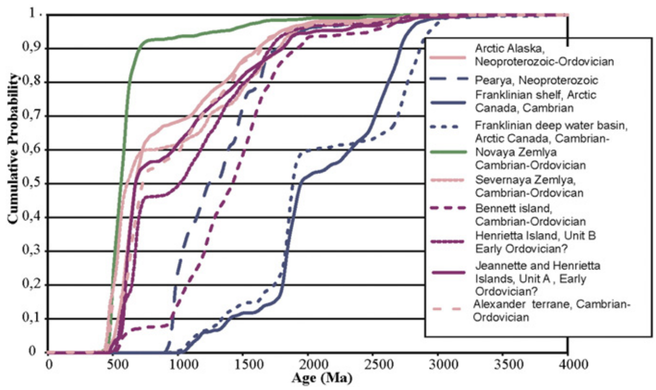


**Fig. 16.** Cumulative probability diagram for samples from this study and for the Lower Paleozoic clastic successions of Severnaya Zemlya (Lorenz et al., 2008), Novaya Zemlya (Lorenz et al., 2013), Pearya, Franklinian deep water basin, Franklinian shelf (Hadlari et al., 2014), Alexander terrane (Beranek et al., 2013) and Seward Peninsula (Amato et al., 2009).

of a several kilometers thick clastic succession of Paleozoic sediments as it is known to exist across the archipelago since no sufficiently large sediment source area is available. Furthermore, the source of these clastics has, based on U–Pb detrital zircon ages, a clear non-Siberian signatures (Ershova et al., 2015a,b; this study).

The fourth model is based on recent U–Pb age studies on detrital zircons from the Upper Paleozoic succession of Kotel'ny and Bel'kovsky islands (Ershova et al., 2015a,b). It suggests that the New Siberian Islands were located along the northern margin of Laurentia and/or Baltica in the Late Paleozoic.

The present study on the Early Paleozoic deposits of the De Long Islands supplies new information that facilitates the geodynamic and plate-tectonic interpretation of this remote Arctic region. In a regional view, the detrital zircon ages from coeval strata around the Arctic (Fig. 16) strongly suggests a common Early Paleozoic history for Severnaya Zemlya, the De Long Islands, Arctic Alaska (Seward Peninsula) and the Alexander Terrane, i.e. that these areas were located close to each other during this period of geological history. Recent geodynamic reconstructions for the Arctic based on detrital zircon data have placed the Seward Peninsula very close to Baltica during the Neoproterozoic and Early Paleozoic (Miller et al., 2010; Till et al., 2010; Miller et al., 2011). The detrital zircon signatures of the Early Paleozoic deposits in the Alexander Terrane also show a robust linkage to the Arctic Alaska–Chukotka Terrane and Baltica, and the Alexander terrane was therefore interpreted to have been a part of a continental margin-fringing arc system along the northeastern margin of Baltica (Beranek et al., 2012, 2013). The new detrital zircon data from the De Long Islands also suggest a strong link to a Baltican provenance (Fig. 16). According to a recent paleomagnetic study by Vernikovsky et al. (2013), the De Long Islands and the Anzhu Islands were part of the same tectonic entity at least since the Early Ordovician (oldest stratigraphic age on Bennett Island), therefore our paleogeographic inferences for the De Long Islands may also apply to the rest of the New Siberian Islands.

The U–Pb dating of zircons from both, the volcanics and the coeval volcaniclastic sedimentary rocks points to latest Cambrian to earliest Ordovician volcanism across the Henrietta and Jeannette islands. The single Ar–Ar age of c. 419 Ma could be interpreted both as the upper age limit for the studied volcanics or as the age of a thermal event across the region in the earliest Devonian, the latter being the more likely. Early Paleozoic volcanics do not occur along the northern margin of Siberia (Parfenov and Kuzmin, 2001). However, volcanics of similar age have been described from several localities across the Arctic including: the Severnaya Zemlya Archipelago (Proskurnin, 1995; Lorenz et al., 2007), Pearya (Arctic Canada; Hadlari et al., 2014), North Slope of Alaska (Moore et al., 1994; Strauss et al., 2013), Seward Peninsula (Arctic Alaska; Amato et al., 2009) and Alexander Terrane (Canadian Cordillera; Beranek et al., 2012). The Pearya, North Slope and Seward Peninsula volcanics are interpreted as volcanic arc related, the Alexander terrane volcanic assemblages as both volcanic arc and back-arc rifting (Amato et al., 2009; Beranek et al., 2012).

The Cambrian–Ordovician successions of the Seward Peninsula, Severnaya Zemlya, Alexander Terrane and De Long Islands are all characterized by continental margin arc volcanics with coeval shallow marine, mainly shelf carbonates. We therefore suggest that they represent the fragments of a single latest Cambrian–earliest Ordovician continental margin arc and back-arc system, which may have been continuous between these locations and that subsequently was dissected by the opening of Late Paleozoic, Mesozoic and Cenozoic oceanic basins (Fig. 17).

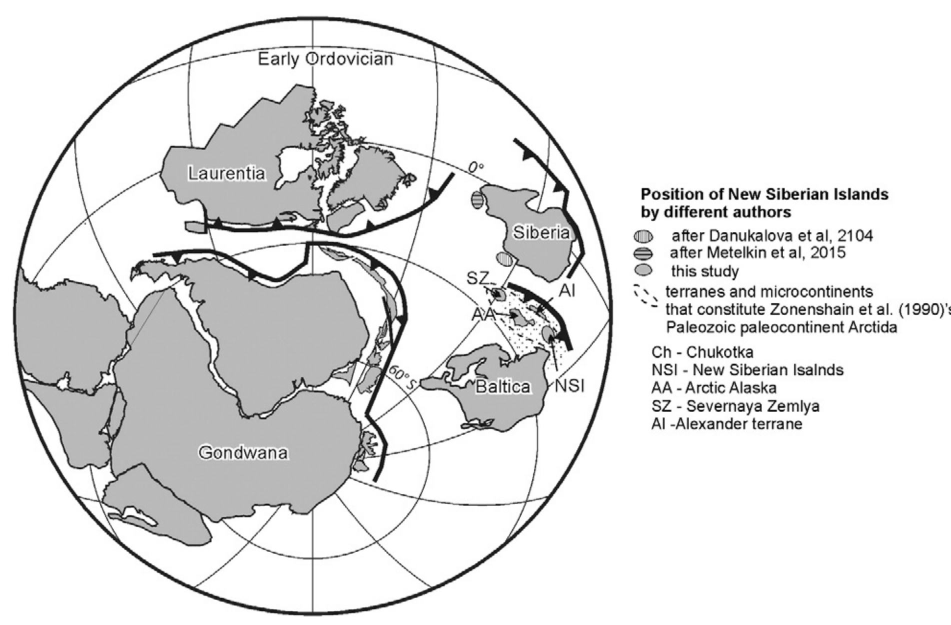


**Fig. 17.** Early Ordovician paleogeographic reconstruction.
Modified from Lawver et al. (2002), Cocks and Torsvik (2005, 2007), Miller et al. (2011), Beranek et al. (2013).

The opening of the Mesozoic Canada Basin in the high Arctic was accompanied by magmatic activity during the Early Cretaceous linked to a High Arctic Large Igneous Province (HALIP), which is manifested onshore in the Canadian Arctic, North Greenland, Svalbard and Franz Josef Land (e.g. Embry and Osadetz, 1988; Tarduno et al., 1998; Maher, 2001; Ntaflos and Richter, 2003; Estrada and Henjes-Kunst, 2004; Buchan and Ernst, 2006; Nejbert et al., 2011; Tegner et al., 2011; Corfu et al., 2013; Døssing et al., 2013; Estrada and Henjes-Kunst, 2013). The basalts which overlay the Early Paleozoic sediments on Bennett Island are interpreted as part of the HALIP (Drachev and Saunders, 2006). Dolerite dykes and sills, which have intruded the early Paleozoic volcaniclastic successions on Jeanette and Henrietta islands, have been dated at ca. 112 Ma and 136 Ma, respectively, and can be considered as equivalents of this volcanism.

## 6. Conclusions and future work

### 6.1. Future work

The tectonic model offered here is based on sedimentology, sedimentary petrography and U–Pb dating of detrital zircons. Further work to test the tectonic models requires more data on Early Paleozoic magmatic rocks across the Arctic to characterize the geochemistry and age of volcanics. This will subsequently improve our understanding of the type and evolution of the magmatism, and, thus, the knowledge base for restoring the arc–back-arc system located along the Baltican margin in Cambrian–Ordovician times.

### 6.2. Conclusions

The new comprehensive data set and interpretations presented here provide new insights into the paleogeography and origin of the little known De Long Islands and refine currently existing models for the Paleozoic paleogeography of the Arctic. The results of our geological study suggest that the De Long Islands represent a Lower Paleozoic active continental margin developed on basement of Timanian age. Sedimentary petrography, facies and composition from the Early Paleozoic successions of Henrietta and Jeannette islands suggest a depositional environment comparable to that of a continental arc–back-arc couplet. The more mature shallow marine Cambrian–Ordovician sediments of Bennett Island were deposited further towards the craton interior, towards the south-west (in present co-ordinates). The primary provenance of the sediments of the De Long Islands are the late Neoproterozoic Timanian, the Early Neoproterozoic–latest Mesoproterozoic Grenville–Sveconorwegian, and the Meso- to Paleoproterozoic Baltic Shield domains. Striking similarities in the detrital zircon age distributions from the Early Paleozoic deposits, along with the development of coeval volcanic complexes, suggest a common Early Paleozoic history for Severnaya Zemlya, the New Siberian Islands, and the Arctic Alaska–Chukotka and Alexander terranes. We suggest that these terranes constituted (part of) a continental margin arc–back-arc–marginal sea environment along the broad Timanian margin of Baltica.

## Acknowledgments

This research was partly supported by RFBR grants N 13-05-00700, 13-05-00943, 15-35-20591, and research grant of Saint Petersburg State University # 3.38.139.2014, in accordance with research program of DMPGI SB RAS N VIII.66.1.4, Integration Project SB RAS N 68 and Project N 53 (RAS N 44P). We are very grateful to crew of the Somov icebreaker for assistance in the field and hospitality. Henning Lorenz acknowledges comprehensive support by the Federal Institute of Geosciences and Natural Resources (BGR), Germany, and thanks for the invitation to the expedition CASE 13 in 2011. This is Nordsim publication number 406. Reviews by two anonymous reviewers and Dr. Alan Aitken (editor) greatly improved the figures and text.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2015.05.016.

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