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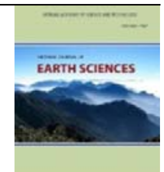

U-Pb detrital zircon geochronology of sedimentary rocks in NE Vietnam: Implication for Early and Middle Devonian Palaeogeography

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ABSTRACT

Rocks of the Do Son Peninsula in NE Vietnam are mainly composed of Palaeozoic siliciclastics. The overall sedimentary record represents fluvial to deltaic prograding deposits close to a shoreline. We present detrital zircon U-Pb analytical results from two samples, the Van Canh and the Van Huong Formations (east Red River Basin). Zircons were analyzed for U, Th, and Pb isotopes by LA-SF ICP-MS techniques. The youngest zircon of each formation provides maximum ages of sedimentation at 407.1 ± 9.5 Ma and 406.3 ± 4.0 Ma. The zircon cluster of both samples supports the postulated position of NE Vietnam close to the western Himalaya.

Keywords: U-Pb detrital zircon; Palaeogeography; Terrane; Van Huong; Van Canh Formations; Vietnam.

1. Introduction

Southeast Asia is composed of a complex puzzle of various terranes (Figure 1) which were rifted from Gondwana during the Early Palaeozoic through the Jurassic times (e.g. Metcalfe, 1984; Burrett and Strait, 1985, 1987; Burrett et al., 1990; Metcalfe, 2011; Usuki et al., 2013). From the Palaeozoic to the Cretaceous several major terranes, including the South China, North China, Indochina, and Sibumasu Terranes amalgamated to form the Southeast Asian tectonic collage (Burrett, 1974; Sengör et al., 1988; Burrett et al., 1991, 2014; Nie, 1991; Hall, 2009; Metcalfe, 2011; Ueno and Charoentitirat, 2011; Morley et al., 2013). The tectonic history of Southeast Asia is very complicated and still matter of discussion (see Morley et al., 2013; Burrett et al., 2014 and references therein).

Two of the largest terranes in Southeast Asia are the Indochina and South China Terranes. The Indochina Terrane is located south of the Song Ma Suture and comprises

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parts of Cambodia, Laos, the eastern peninsular of Malaysia, northern Thailand, and parts of Vietnam. The South China Terrane is present north of this suture zone (Helmcke, 1985; Finlay, 1997; Sone and Metcalfe, 2008; Metcalfe, 2011; Burrett et al., 2014; Figure 1) and consists of NE Vietnam, Cathaysia, Ailaoshan and the Yangtze Terrane (Burrett et al., 2014). The Song Da Terrane which is sandwiched between the Song Ma Suture in the southwest and the Red River Fault Zone (RRFZ) in the northeast may be roughly correlated with the West Red River Basin of Tri and Khuc (2011). The RRFZ strikes NW-SE and represents a major Cenozoic left-lateral shear zone as a result of the continental extrusion of Indochina (Tapponnier et al., 1990). East of the RRFZ NE Vietnam may be correlated with the East Red River Basin published in Tri and Khuc (2011; Figure 1). NE Vietnam has also been considered as a nappe structure (Faure et al., 2014) which is geologically similar to the South China Continental Margin (e.g., Lepvrier et al., 2011; Tri and Khuc, 2011).

The evolution of the Indochina- and South China Terranes during the Early Palaeozoic is the still matter of discussion. Torsvik and Cocks (2009) believe that the Indochina- and South China Terranes existed as isolated blocks during the Early Palaeozoic, but other authors suggest that both terranes were part of the India-Australian margin of Gondwana (Metcalfe, 1998, 2006, 2011; Usuki et al., 2013). According to Burrett et al. (2014), NE Vietnam was part of the Southern China Terranes (Ailaoshan, NE Vietnam, Yangtze) during the early Palaeozoic. Depositional facies settings of Late and Middle Devonian siliciclastics in NE Vietnam are comparable to those along the southeastern coast of China (e.g. Jones et al., 1997) and they also yield the same vertebrate remains (Yang et al., 1981; Lee, 1991; Jones et al., 1997; Janvier et al., 2003).

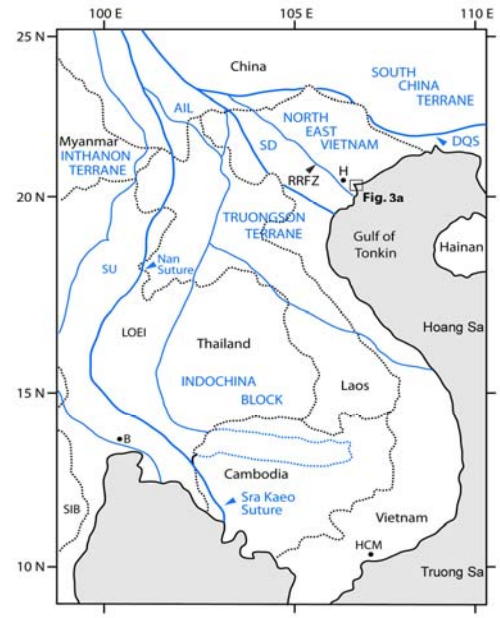

Figure 1. Tectonic framework of SE Asia (adapted from Lepvrier et al., 2004; Sone and Metcalfe 2008; Metcalfe 2011; Burrett et al., 2014) and sample locality southeast of Hanoi (see also Figures 3a, b). Bold blue lines indicate main suture zones or faults, stippled lines indicate country boundaries. Abbreviations: AIL = Ailaoshan Terrane; DQS = Dian Qiong Suture; LOEI = Loei Petchabun Foldbelt; RRFZ = Red River Fault Zone; SMS = Song Ma Suture; SD = Song Da Terrane; SIB = Sibumasu; SU = Sukhothai; B = Bangkok; H = Hanoi; HCM = Ho Chi Minh City

In this paper, we present U-Pb detrital zircon ages of siliciclastic rocks from two formations in NE Vietnam and discuss the results with paleo(bio)geographic affinities and derivations of Devonian siliciclastics in southern China.

2. Geological setting

The study area is located on the Do Son Peninsula (N20°42’36,1’’; E106°47’02,4’’) in the southern part of northeast Vietnam (Figure 1). In terms of structural units this area belongs to the Early Palaeozoic eastern part of the Red River Basin (Tri and Khuc, 2011; Figures 1, 2). Nam (1995) used the term “NE

Block" for the same area. In the East Red River Basin, Silurian rocks are conformably overlain by Devonian rocks of the Do Son Group. The overlying sediments belong to the Thuy Nguyen Group including formations of the Trang Kenh- and the Early Carboniferous, Con Voi, and Pho Han Formations (Figure 2). Further to the west, Devonian deposits are dominated by carbonates, representing shelf facies in the Middle Devonian and more pelagic facies in the Upper Devonian sediments. Pelagic facies settings in the Late Devonian and Early Carboniferous are found in the east part of the described section, on Cat Ba Island as well as in the northeastern part of Vietnam (Dong Van area) close to the border of China (e.g. Komatsu et al., 2014; Königshof et al., 2017 and references therein).

The Do Son Group that was established by Lantenois (1907) includes the Early to Middle Devonian Van Canh and Duong Dong Formations as well as the Middle Devonian Van Huong Formation (e.g., Tong-Dzuy, 1986; Long et al., 1990). In other publications (e.g., Janvier et al., 2003) the siliciclastics of the Do Son Peninsula were considered to belong to one formation, namely the Do Son Formation which has been subdivided in two members: the older one is Silurian or Early Lochkovian in age, and the younger one is Givetian in age. Herein, we prefer to use the terminology "Do Son Group" published in Tri and Khuc (2011, see Figure 2). The Do Son Group is mainly composed of siliciclastic sediments representing littoral to neritic facies settings and can be subdivided into two formations, the Van Canh- and the Van Huong Formations, respectively. The reason for the subdivision is based on the improved biostratigraphy of the relevant sediments (e.g., Tong-Dzuy et al., 1994). The Van Canh Formation has its stratotype in the west side of the Van Canh Island and has a thickness of ~500 m. It lies conformably on the Silurian Kien An Formation and represents a nearshore environment (Tri and Khuc, 2011). Sediments of the study area at the Do Son Peninsula (Figure 3a, b) are mainly composed of greenish-grey to light grey medium-bedded siltstones, brownish-grey, medium-bedded sandstones and rare quarzites. Occasionally, coarser-grained sandstones and conglomerates are present (Figure 4). The rocks contain a number of fossils, such as fishes (e.g. *Yunnanolepis*, *Zhanjilepis* and W*angolepis*), plants (e.g. *Cooksonia*, *Sporogonites* cf. *yunnanense* and cf. *Filiformorama* sp.), and eurypterids (*Rhynocarcinosoma dosonensis*, *Hyghmilleria* sp.) and were described in detail by Janvier et al. (1987, 2003) and Braddy et al. (2002). The series of siliciclastic sediments of the Do Son Peninsula have been included within the Do Son Formation (Janvier et al., 2003). The presence of eurypterid *Rhinocarcinosoma* sp. in *Cooksonia*-bearing layers may support a Silurian age, at the basal part of the Do Son Formation (see Janvier et al., 2003, Braddy et al., 2002). Tri and Khuc (2011) recently attributed the Van Canh Formation to Early- to Middle Devonian (Emsian to Eifelian) age synchronous with the Duong Dong Formation (Figure 2).

Thin-bedded, argillaceous sandstones and siltstones of the Van Canh Formation are disconformably overlain by the Van Huong Formation outcropping in Xom Che (Figure 3), which exhibit erosive channel features. The Van Huong Formation has its stratotype in the Ba Vi mountain on the western side of the Do Son Peninsula and has a thickness of ~70 m. Rocks of this formation are mainly medium- to thick-bedded siltstones, cross-bedded sandstones and quartzitic sandstones and contain a number of fossils, such as fishes (*Vietnamaspis trii*, *Briagalepis* sp., *Bothriolepis* sp. (cf. *B. gigantea*)) and plants such as *Bergeria* or *Knorria* (cf. *Lepidodendropsis* sp.). Based on the collected *Lepidodendropsis*-*Bothriolepis* assemblage, the Van Huong Formation was considered to be Middle Devonian (Givetian, see Long et al., 1990) in age, and overlying massive sandstones may also extend into the early Late Devonian (Janvier et al., 2003). The overall sedimentary record mainly represents fluvial to deltaic prograding deposits close to a shoreline and are very similar to deposits of the same age known from South China (Xun et al., 1996; Jones et al., 1997).

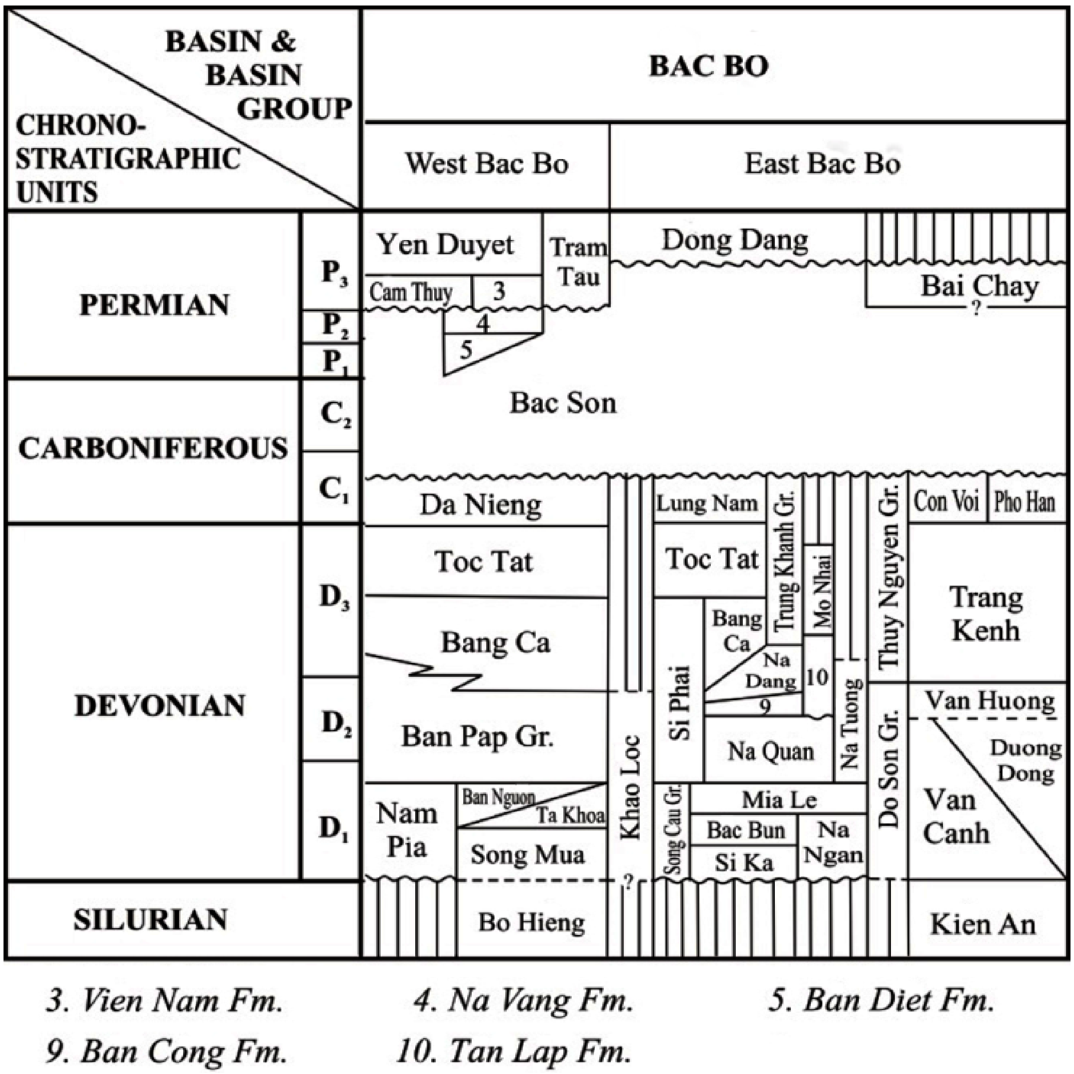

Figure 2. Schema of subdivision and correlation of stratigraphic units of the Devonian-Upper Permian (Wuchiapingian) Supersequence (Tri and Khuc, 2011, with minor adaptions)

The Devonian red-coloured sediments are found in the Hue area while marine sediments of the same age are found in the west, in the center of the Red River Basin. This indicates that the Lower and Middle Devonian, primarily terrigenous sediments in northeastern Vietnam are progressively replaced to the west by carbonate sedimentation (Nam, 1995; Janvier et al., 2003).

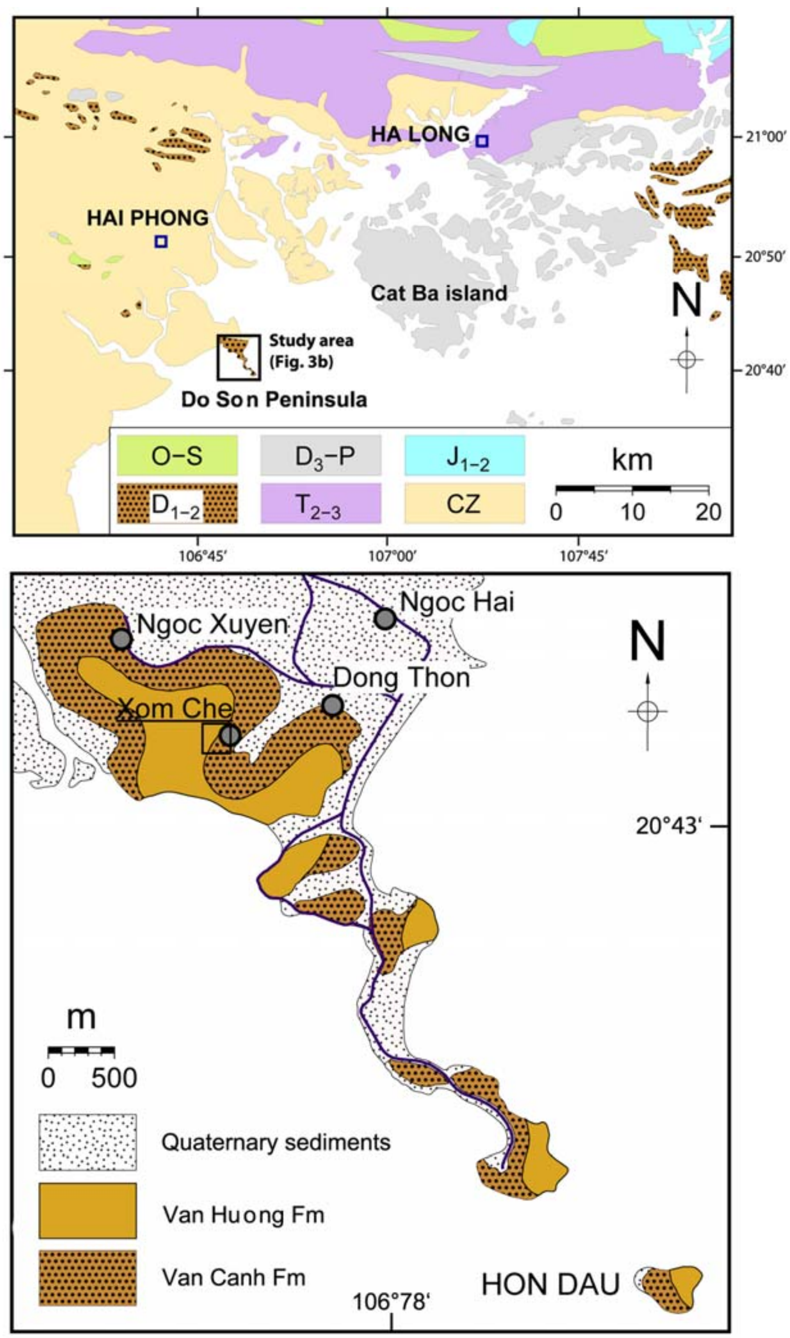

Figure 3. (a) Simplified geological map of the southern part of NE Vietnam: O-S: Ordovician to Silurian; D_{1-2}: Early and Middle Devonian; D_3-P: Late Devonian to Permian; T_{2-3}: Early and Middle Triassic; J_{1-2}: Early and Middle Jurassic; CZ: Cenozoic; (b) Geological map the Do Son Peninsula showing the Xom Che section from this study. The quadrant shows the study area

3. Analytical techniques

Zircons have been extracted from a conglomeratic sandstone of the Van Huong Formation (sample VN23-2012) and a quarzitic sandstone of the underlying Van Canh Formation (sample VN24-2012; Figure 4). Zircons were separated from 2-4 kg samples at the *Senckenberg Naturhistorische Sammlungen Dresden (Museum für Mineralogie und Geologie)* using standard magnetic and density methods. Final selection of the zircon grains for U-Pb dating was achieved by handpicking under a binocular microscope. Zircon grains of all grain sizes and morphological types were selected, mounted in epoxy resin and polished to reveal the core for cathodoluminescence (CL) investigation and U-Pb isotope analysis. The stratigraphic time scale of Ogg et al. (2016) was used for stratigraphic age correlation.

Zircons were analyzed for U, Th, and Pb isotopes by LA-SF ICP-MS techniques at the Museum für Mineralogie und Geologie (GeoPlasma Lab, Senckenberg Naturhistorische Sammlungen Dresden), using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. A teardrop-shaped, low volume laser cell was used to enable sequential sampling of heterogeneous grains (e.g., growth zones) during time resolved data acquisition. Each analysis consisted of approximately 15s background acquisition followed by 30 s data acquisition, using a laser spot-size of 25 µm and 35 µm, respectively. A common-Pb correction based on the interference and background-corrected ^{204}Pb signal and a model Pb composition (Stacey and Kramers, 1975) was carried out when necessary. The necessity of the correction was judged on whether the corrected ^{207}Pb/^{206}Pb lay outside of the internal error of the measured ratios. Discordant analyses were interpreted with care, whereas raw data were corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination, and time-dependant elemental fractionation of Pb/Th and Pb/U using an Excel® spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann Wolfgang Goethe-University Frankfurt, Frankfurt am Main, Germany). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (~0.6% and 0.5-1% for the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U, respectively) during individual analytical sessions and the within-run precision of each analysis. According to the recommendation of Horstwood et al. (2016) a secondary zircon standard (Plešovice zircon) was analysed. Sequences started with the analysis of five GJ1, one Plešovice and 10 unknowns followed by a repetition of a succession of three measurements of the GJ1 standard, one measurement of the Plešovice standard and 10 unknowns. Measured U-Pb ages of the primary standard GJ1 zircon (606±4 Ma, n=66) and the secondary Plešovice standard zircon (340±6 Ma, n=20) were within error in the recommended ranges of Jackson et al. (2004) and Sláma et al. (2008).

Concordia diagrams (2σ error ellipses) and Concordia ages (95% confidence level) were produced using Isoplot/Ex 2.49 (Ludwig, 2001) and frequency and relative probability plots using AgeDisplay (Sircombe, 2004). The ^{207}Pb/^{206}Pb age was taken for interpretation for all zircons >1.0 Ga, and the ^{206}Pb/^{238}U ages for younger grains. For further details on analytical protocol and data processing see Gerdes and Zeh (2006). Th/U ratios were obtained from the LA-ICP-MS measurements of investigated zircon grains. U and Pb content and Th/U ratio were calculated relative to the GJ-1 zircon standard and are accurate to approximately 10%.

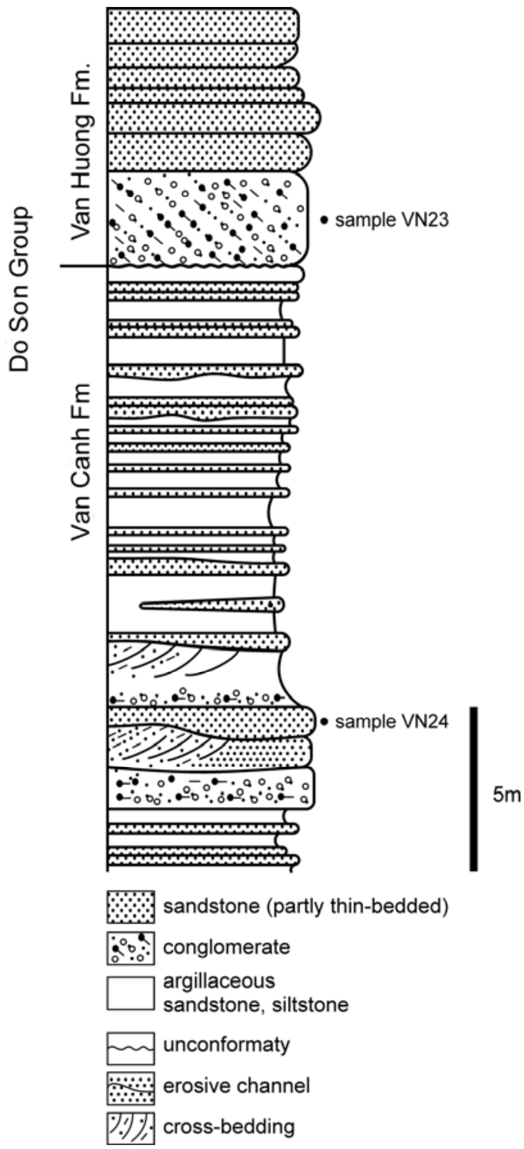

Figure 4. Lithological log of the Xom Che section on the Do Son Peninsula and position of samples VN24, and VN23. Conglomerates, sandstones (partly cross-bedded), and quartzites of the Middle Devonian Van Huong Formation unconformably overlay thin-bedded, argillaceous sandstones and siltstones of the Silurian(?) to Early Devonian Van Canh Formation (Janvier et al., 2003, with minor adaptions)

4. Analytical results

4.1. Representative CL images from analysed samples

Cathodoluminescence images (CL) of selected zircon grains are displayed in Figure 5. Zircon grains of samples VN23 and VN24 range from 85 to 240 µm in length. Our study provides numerous Cambrian and Ordovician zircon U-Pb ages and some of them are euhedral in shape (VN24-a41 and VN24-b16, Figure 5), but this does not necessarily mean that they did underwent short-distance transport (this may also depend on the time of exhumation of magmatic or metamorphic rocks). Most zircons are sub-to well-rounded and show clear magmatic zoning. Roundness points to moderate transport distances in a fluvial or shallow marine environment.

Most zircons are clear and colourless to yellowish and transparent. Needle-like zircon grains are scarce (VN24-a47, Figure 5). Complex zircon grains showing rims and cores are scarce in sample VN23 whereas they are more frequent in sample VN24 (VN24-a13, Figure 5). A number of complex zircon grains aged around 950-1100 Ma occur in both investigated samples (e.g. VN23-c02). A few 2280-2377 Ma old zircon grains are characterized by pale rims depleted in Uranium, which were derived from rocks that underwent high pressure metamorphic conditions (grains VN24-a51, VN24-b05, Figure 5).

4.2. Zircon dating

Two rock samples (sample VN23-2012, and sample VN24-2102) provided 205 zircons that were selected for U-Pb dating. Analytical results of U-Th-Pb isotopes and calculated U-Pb ages are given in Tables 1 and 2. Age ranges and percentages of detrital zircons in samples VN23 and VN 24 are given in Table 3.

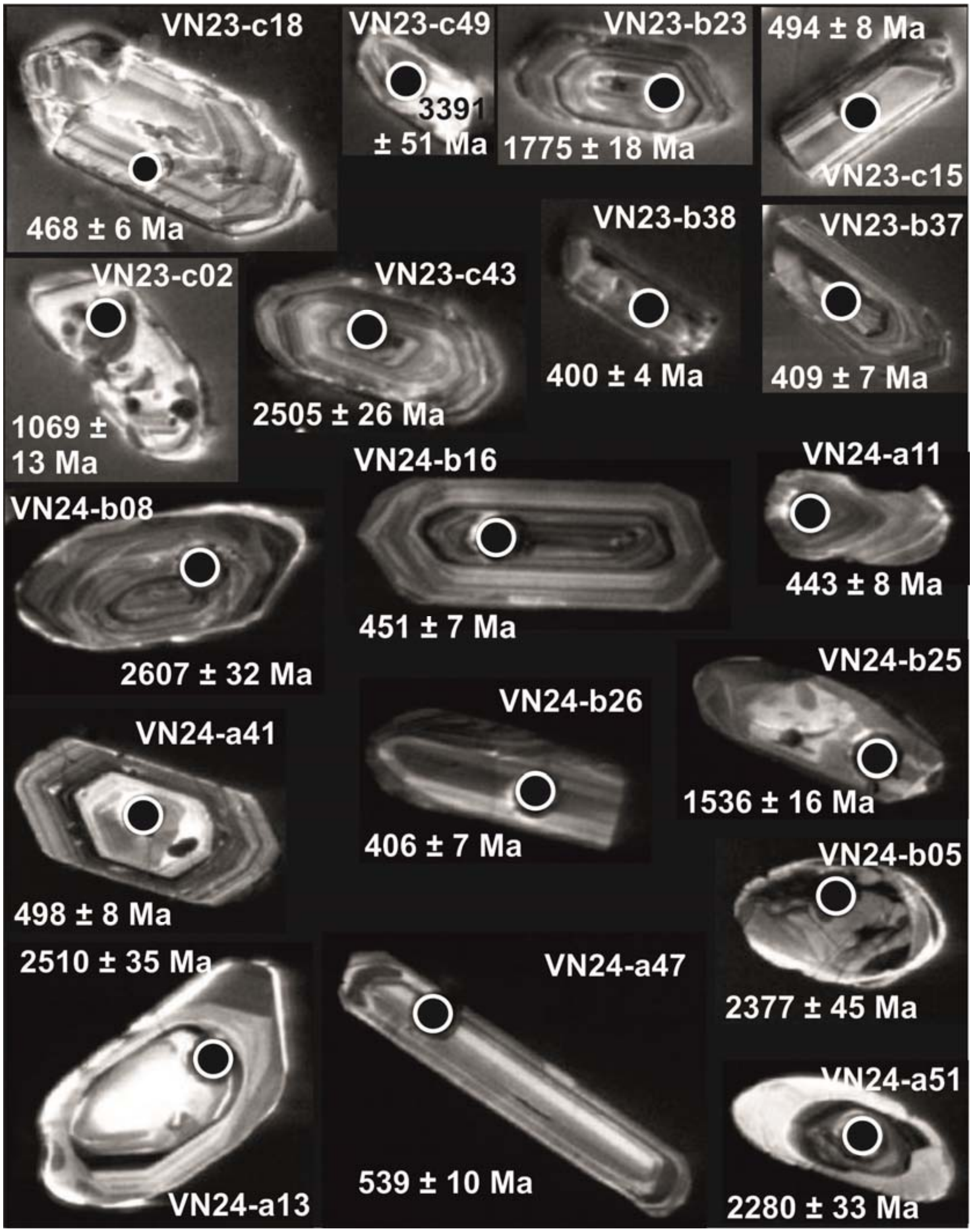

Figure 5. Cathodoluminescence images of selected zircon grains of samples VN23 and VN24. Spot diameter is 25µ

Table 1. Zircon U-Pb analytical data of sample VN23, n = 109 of 120 measured zircon grains, conglomeratic sandstone (Do Son group, Van Huong Formation, Middle Devonian; location: Do Son Peninsula, Vietnam: (N20° 42’36,1’’; E106°47’02,4’’)

Number	$^{207}Pb^a$ (cps)	U^b (ppm)	Pb^b (ppm)	$\frac{Th^b}{U}$	$\frac{^{206}Pb^c}{^{204}Pb}$	$\frac{^{206}Pb^c}{^{238}U}$	2 σ %	$\frac{^{207}Pb^c}{^{235}U}$	2 σ %	$\frac{^{207}Pb^c}{^{206}Pb}$	2 σ %	rho^d	$\frac{^{206}Pb}{^{238}U}$	2 σ (Ma)	$\frac{^{207}Pb}{^{235}U}$	2 σ (Ma)	$\frac{^{207}Pb}{^{206}Pb}$	2 σ (Ma)	conc %
b38	9240	197	12	0.07	17116	0.06406	2.1	0.48366	6.2	0.05476	5.9	0.34	400	8	401	21	402	131	99
b20	12096	198	14	0.42	3534	0.06461	2.6	0.49141	4.2	0.05517	3.3	0.61	404	10	406	14	419	75	96
b13	24873	398	27	0.36	2659	0.06545	2.0	0.49546	3.3	0.05490	2.6	0.62	409	8	409	11	408	57	100
b37	10428	221	16	0.53	18941	0.06556	3.3	0.50556	4.8	0.05593	3.4	0.69	409	13	415	16	450	77	91
c29	23202	256	18	0.52	3053	0.06558	2.6	0.49731	3.7	0.05500	2.6	0.70	409	10	410	12	412	59	99
c44	22600	346	24	0.32	41651	0.06543	3.3	0.49856	3.9	0.05526	2.1	0.84	409	13	411	13	423	48	97
c40	15315	211	15	0.27	23688	0.06800	2.7	0.52195	3.1	0.05567	1.6	0.86	424	11	426	11	439	36	97
b47	8277	201	15	0.41	15205	0.06821	3.4	0.52255	4.8	0.05556	3.4	0.71	425	14	427	17	435	75	98
b19	32280	417	30	0.34	58044	0.06855	2.0	0.53418	2.2	0.05652	0.7	0.94	427	8	435	8	473	17	90
b43	6358	139	9	0.22	11572	0.06849	2.6	0.52605	4.0	0.05571	3.0	0.66	427	11	429	14	441	68	97
c12	37937	425	31	0.38	11655	0.06907	3.4	0.53109	4.2	0.05577	2.4	0.82	431	14	433	15	443	54	97
c16	22708	276	22	0.61	8586	0.06908	2.7	0.52934	3.2	0.05557	1.8	0.84	431	11	431	11	435	39	99
b40	12935	254	19	0.40	23523	0.06966	2.3	0.53686	3.2	0.05589	2.1	0.73	434	10	436	11	448	48	97
c21	69039	519	39	0.29	2504	0.06976	3.4	0.53813	3.6	0.05595	1.3	0.93	435	14	437	13	450	29	97
b50	20881	515	38	0.32	37772	0.07102	3.0	0.54981	3.9	0.05615	2.4	0.78	442	13	445	14	458	54	96
b58	7593	206	15	0.29	13759	0.07103	2.6	0.54943	3.3	0.05610	2.2	0.77	442	11	445	12	456	48	97
b41	8778	220	17	0.39	15780	0.07110	2.5	0.55319	3.4	0.05643	2.3	0.74	443	11	447	12	469	50	94
b45	11178	271	20	0.31	20379	0.07109	2.6	0.54665	3.9	0.05577	2.9	0.67	443	11	443	14	443	65	100
c39	18780	264	20	0.37	34158	0.07126	3.0	0.54912	3.7	0.05589	2.2	0.80	444	13	444	14	448	50	99
c17	8409	89	7	0.42	14831	0.07193	2.8	0.55701	3.4	0.05616	1.9	0.83	448	12	450	12	459	42	98
c33	35564	461	35	0.29	39095	0.07358	2.8	0.56936	3.3	0.05612	1.7	0.85	458	12	458	12	457	38	100
a6	18384	219	16	0.28	33020	0.07390	1.7	0.57568	2.0	0.05650	0.9	0.89	460	8	462	7	472	20	97
c32	26474	340	25	0.22	11354	0.07399	2.8	0.57467	3.6	0.05633	2.2	0.79	460	13	461	13	466	49	99
c14	17991	205	15	0.24	32363	0.07417	2.8	0.57761	3.3	0.05648	1.8	0.85	461	13	463	12	471	39	98
b32	9386	170	13	0.39	16769	0.07468	2.6	0.58238	5.7	0.05656	5.0	0.45	464	12	466	21	474	111	98
b55	8668	229	18	0.35	15611	0.07478	2.4	0.58142	3.4	0.05639	2.4	0.71	465	11	465	13	468	52	99
c31	16079	222	17	0.40	10133	0.07502	2.9	0.58516	3.5	0.05657	2.1	0.81	466	13	468	13	475	46	98
b3	13794	198	15	0.37	8281	0.07511	2.3	0.59127	3.2	0.05709	2.3	0.70	467	10	472	12	495	50	94
b54	12904	335	25	0.22	23308	0.07515	2.4	0.58437	3.7	0.05640	2.7	0.66	467	11	467	14	468	61	100
b53	7700	177	14	0.38	3912	0.07535	2.6	0.59396	6.2	0.05717	5.7	0.41	468	12	473	24	498	126	94
c18	7980	92	7	0.32	14136	0.07528	2.8	0.59613	3.4	0.05743	1.9	0.83	468	13	475	13	508	42	92
b33	4505	88	8	0.64	5576	0.07552	2.3	0.58862	4.4	0.05653	3.7	0.53	469	10	470	17	473	82	99
a7	7469	75	6	0.45	1460	0.07563	2.0	0.58978	4.4	0.05656	4.0	0.44	470	9	471	17	474	88	99
a8	20677	258	20	0.27	21145	0.07573	1.7	0.58984	3.1	0.05649	2.6	0.56	471	8	471	12	472	57	100
c50	17715	272	21	0.23	31793	0.07574	3.9	0.59216	4.6	0.05671	2.4	0.85	471	18	472	17	480	53	98
b42	9459	167	14	0.44	16780	0.07602	2.4	0.60004	3.5	0.05724	2.5	0.70	472	11	477	13	501	54	94
c11	13914	152	12	0.28	24983	0.07603	3.2	0.59195	3.8	0.05647	2.1	0.84	472	15	472	15	471	46	100
b28	13190	211	16	0.14	23567	0.07670	2.2	0.60179	2.8	0.05690	1.7	0.79	476	10	478	11	488	37	98
b30	12907	233	19	0.56	23149	0.07667	3.0	0.59948	4.5	0.05671	3.3	0.67	476	14	477	17	480	73	99
c22	8658	97	8	0.54	5150	0.07656	3.0	0.59700	4.7	0.05656	3.6	0.64	476	14	475	18	474	79	100
b51	4665	111	9	0.32	6216	0.07675	2.6	0.60730	5.2	0.05739	4.5	0.50	477	12	482	20	506	99	94
c1	7782	71	7	0.77	13797	0.07677	2.9	0.60455	4.3	0.05712	3.1	0.68	477	13	480	16	496	69	96
c23	19571	235	19	0.34	7623	0.07687	2.8	0.60308	3.3	0.05690	1.7	0.85	477	13	479	13	488	38	98
c30	7044	81	7	0.51	12602	0.07700	3.1	0.60483	4.8	0.05697	3.7	0.64	478	14	480	19	490	81	98
b15	4257	61	5	0.45	7590	0.07734	2.1	0.60858	3.6	0.05707	2.9	0.59	480	10	483	14	494	64	97
b18	8455	118	9	0.26	15195	0.07722	2.4	0.60663	13.6	0.05697	13.4	0.18	480	11	481	54	491	296	98
b21	23377	417	33	0.45	4376	0.07735	2.6	0.60594	3.3	0.05682	2.0	0.80	480	12	481	13	484	43	99
b57	3740	95	8	0.42	6639	0.07726	2.5	0.60918	4.7	0.05718	4.0	0.52	480	11	483	18	499	88	96
a1	7229	96	8	0.39	6827	0.07771	2.4	0.61336	3.0	0.05724	1.9	0.78	482	11	486	12	501	42	96
b27	11280	167	13	0.14	14484	0.07818	2.4	0.61805	3.3	0.05733	2.2	0.74	485	11	489	13	504	49	96
b10	9732	141	11	0.29	17282	0.07825	2.1	0.61611	5.1	0.05710	4.6	0.40	486	10	487	20	496	102	98
b5	10435	149	13	0.51	18609	0.07864	3.8	0.61854	5.0	0.05704	3.2	0.77	488	18	489	19	493	70	99
c45	7774	108	9	0.23	2456	0.07909	3.1	0.62292	3.7	0.05712	2.1	0.82	491	15	492	15	496	47	99

b12	5919	85	7	0.29	10489	0.07941	2.6	0.62618	4.0	0.05719	3.0	0.66	493	12	494	16	499	67	99
c3	10098	95	9	0.57	17791	0.07968	3.0	0.63427	4.8	0.05773	3.7	0.64	494	14	499	19	520	81	95
c15	9115	89	8	0.39	16242	0.07969	3.2	0.62704	3.9	0.05707	2.2	0.82	494	15	494	15	494	49	100
b31	5610	103	9	0.45	9888	0.08042	2.7	0.63827	7.7	0.05756	7.3	0.34	499	13	501	31	513	160	97
b52	19621	391	38	0.53	18053	0.08712	3.3	0.70977	3.8	0.05909	1.8	0.88	538	17	545	16	570	39	94
c5	11309	119	12	0.87	440	0.09037	2.8	0.73995	6.0	0.05939	5.3	0.46	558	15	562	26	581	115	96
b1	4807	59	6	0.41	4464	0.09547	1.9	0.78555	9.8	0.05967	9.6	0.19	588	10	589	45	592	208	99
c4	10498	78	8	0.23	17639	0.09969	3.7	0.82948	4.6	0.06034	2.7	0.81	613	22	613	22	616	59	99
c37	15024	129	15	0.45	25045	0.10350	3.0	0.86903	3.6	0.06090	1.9	0.85	635	18	635	17	636	41	100
b36	6375	75	9	0.33	10406	0.11107	2.5	0.95219	4.3	0.06218	3.5	0.58	679	16	679	21	680	74	100
c10	37845	207	29	0.80	1413	0.11307	3.0	0.98677	4.0	0.06330	2.5	0.77	691	20	697	20	718	54	96
b60	8701	142	18	0.54	13798	0.11506	2.1	1.01722	4.1	0.06412	3.5	0.52	702	14	713	21	746	74	94
b49	7030	79	13	1.21	11232	0.11702	2.9	1.02113	4.7	0.06329	3.7	0.62	713	20	714	24	718	78	99
b26	7123	57	10	0.96	11087	0.12363	4.7	1.11078	7.4	0.06516	5.7	0.63	751	33	759	40	780	121	96
a3	19269	106	13	0.35	29298	0.12549	2.1	1.15922	2.9	0.06700	2.0	0.72	762	15	782	16	838	42	91
c38	15308	122	19	0.50	16917	0.14109	2.8	1.31767	4.0	0.06773	2.8	0.71	851	23	853	23	860	58	99
b24	14347	110	20	0.96	21315	0.14379	2.3	1.35643	2.8	0.06842	1.5	0.83	866	19	870	16	881	32	98
c35	24908	136	21	0.31	10028	0.14713	3.2	1.41194	4.1	0.06960	2.6	0.78	885	26	894	25	917	53	97
b2	15212	77	13	0.47	22034	0.15056	3.0	1.45627	3.8	0.07015	2.4	0.77	904	25	912	23	933	50	97
b29	6277	35	7	1.03	9050	0.15388	2.8	1.49229	5.6	0.07034	4.8	0.51	923	24	927	35	938	99	98
c8	25655	107	20	0.52	36359	0.16094	2.8	1.59844	3.3	0.07203	1.7	0.85	962	25	970	21	987	35	97
b22	40883	407	62	0.15	56775	0.16114	2.6	1.63117	3.9	0.07342	2.9	0.67	963	23	982	25	1026	58	94
b11	84172	478	80	0.32	21121	0.16130	2.8	1.59912	3.2	0.07190	1.6	0.87	964	25	970	20	983	32	98
c47	91234	490	79	0.25	6219	0.16220	2.6	1.60812	3.2	0.07191	1.9	0.80	969	23	973	20	983	39	99
b8	35027	169	30	0.41	49368	0.16247	2.2	1.61489	2.7	0.07209	1.6	0.82	971	20	976	17	988	32	98
c13	57925	221	40	0.43	81587	0.16594	2.8	1.65029	3.1	0.07213	1.4	0.89	990	25	990	20	990	29	100
c34	34857	156	30	0.49	18600	0.17380	3.2	1.79069	4.0	0.07473	2.3	0.81	1033	31	1042	26	1061	47	97
b16	11254	48	11	0.96	15409	0.17657	2.4	1.80454	3.8	0.07412	2.9	0.64	1048	24	1047	25	1045	59	100
b9	24566	110	21	0.44	33687	0.17664	2.2	1.80499	2.7	0.07411	1.6	0.81	1049	22	1047	18	1044	32	100
c2	31933	108	19	0.15	43805	0.18029	2.7	1.84170	3.0	0.07409	1.4	0.88	1069	26	1060	20	1044	29	102
c48	50730	247	49	0.39	68274	0.18034	2.9	1.87705	3.2	0.07549	1.3	0.92	1069	29	1073	21	1082	26	99
c24	126515	470	82	0.12	30177	0.18181	2.6	1.88881	2.9	0.07535	1.2	0.91	1077	26	1077	19	1078	24	100
b46	10415	80	18	0.82	13965	0.18213	2.2	1.90864	3.5	0.07600	2.7	0.63	1079	22	1084	23	1095	54	98
b34	5868	37	7	0.63	7352	0.18453	2.6	1.99016	7.6	0.07822	7.1	0.34	1092	26	1112	53	1152	142	95
c20	30855	94	22	0.83	40148	0.18489	2.9	1.98970	3.9	0.07805	2.5	0.76	1094	30	1112	26	1148	50	95
b14	27313	114	23	0.43	36441	0.18544	2.4	1.94603	3.3	0.07611	2.2	0.74	1097	24	1097	22	1098	44	100
c42	80693	327	73	0.63	5567	0.18579	2.8	1.97393	3.4	0.07706	2.0	0.82	1099	29	1107	23	1123	39	98
b25	3178	17	3	0.31	4008	0.18884	2.5	2.07322	11.9	0.07963	11.6	0.21	1115	25	1140	85	1188	229	94
a4	23696	69	18	1.17	30918	0.19384	2.4	2.07776	3.2	0.07774	2.0	0.77	1142	25	1141	22	1140	40	100
c41	14156	50	13	0.88	18000	0.20036	4.4	2.20762	4.8	0.07991	2.0	0.91	1177	47	1183	34	1195	39	99
c19	41031	106	28	0.84	51886	0.20227	3.2	2.23365	3.7	0.08009	1.9	0.86	1187	35	1192	26	1199	38	99
b17	24945	70	20	0.72	15755	0.23802	2.4	2.87190	3.0	0.08751	1.8	0.79	1376	30	1375	23	1372	35	100
c28	139381	389	107	0.54	8792	0.24815	2.7	3.09497	3.1	0.09046	1.5	0.87	1429	35	1431	24	1435	29	100
b39	10398	35	14	1.69	11350	0.25251	2.8	3.23544	3.7	0.09293	2.4	0.75	1451	36	1466	29	1486	46	98
c36	98148	211	61	0.83	4771	0.27020	3.3	3.67386	3.8	0.09861	1.9	0.87	1542	45	1566	31	1598	35	96
b44	20776	68	23	1.03	4467	0.28452	2.2	3.97263	2.6	0.10127	1.5	0.82	1614	31	1629	22	1647	28	98
c46	165247	331	104	0.34	37977	0.29087	3.5	4.06053	4.2	0.10125	2.4	0.83	1646	51	1646	35	1647	44	100
c9	31121	42	14	0.37	30876	0.29370	2.6	4.14834	3.5	0.10244	2.4	0.74	1660	38	1664	29	1669	44	99
b35	17232	42	15	0.67	16555	0.30133	2.7	4.38985	3.2	0.10566	1.7	0.84	1698	40	1710	27	1726	32	98
b23	51782	104	33	0.17	49762	0.31690	2.3	4.62523	40.1	0.10585	40.0	0.06	1775	36	1754	406	1729	734	103
c7	164253	208	76	0.41	146745	0.32323	3.3	5.06962	3.5	0.11375	1.1	0.95	1805	52	1831	30	1860	20	97
b56	121788	207	113	0.56	77982	0.45765	3.1	10.01660	3.3	0.15874	1.2	0.93	2429	63	2436	31	2442	21	99
c6	360239	234	135	0.83	225570	0.47007	2.6	10.52845	2.9	0.16244	1.3	0.90	2484	55	2482	28	2481	22	100
c43	238053	184	112	0.67	138532	0.47496	2.5	11.45528	4.5	0.17492	3.7	0.57	2505	53	2561	42	2605	61	96
b4	113652	81	46	0.53	31352	0.47527	2.3	10.97481	2.6	0.16748	1.2	0.88	2507	47	2521	24	2533	20	99
c49	168836	50	48	0.73	59281	0.69227	4.0	27.59714	4.2	0.28913	1.2	0.96	3391	107	3405	42	3413	18	99

[a]within-run background-corrected mean ^{207}Pb signal in counts per second; [b]U and Pb content and Th/U ratio were calculated relative to GJ-1 and are accurate to approximately 10%; [c]corrected for background, mass bias, laser induced U-Pb fractionation and common Pb (if detectable, see analytical method) using Stacey & Kramers (1975) model Pb composition. $^{207}Pb/^{235}U$ calculated using $^{207}Pb/^{206}Pb/(^{238}U/^{206}Pb \times 1/137.88)$. Errors are propagated by quadratic addition of within-run errors (2SE) and the reproducibility of GJ-1 (2SD); [d]Rho is the error correlation defined as err$^{206}Pb/^{238}U$/err$^{207}Pb/^{235}$

Table 2. Zircon U-Pb analytical data of sample VN24, n = 96 of 120 measured zircon grains, sandstone (Do Son group, Van Canh Formation, Early Devonian; location: Do Son Peninsula, Vietnam: (N20°42'36,1''; E106°47'02,4'')

Number	$^{207}Pb^a$ (cps)	U^b (ppm)	Pb^b (ppm)	$\frac{Th^b}{U}$	$\frac{^{206}Pb^c}{^{204}Pb}$	$\frac{^{206}Pb^c}{^{238}U}$	2 σ %	$\frac{^{207}Pb^c}{^{235}U}$	2 σ %	$\frac{^{207}Pb^c}{^{206}Pb}$	2 σ %	rho[d]	$\frac{^{206}Pb}{^{238}U}$	2 σ (Ma)	$\frac{^{207}Pb}{^{235}U}$	2 σ (Ma)	$\frac{^{207}Pb}{^{206}Pb}$	2 σ (Ma)	conc %
a26	5134	123	8	0.35	9504	0.06505	3.6	0.49377	4.7	0.05506	3.0	0.78	406	14	407	16	414	66	98
c7	25486	516	34	0.31	15818	0.06507	2.5	0.50589	4.0	0.05639	3.2	0.62	406	10	416	14	468	70	87
a17	23382	495	34	0.28	43515	0.06525	5.1	0.49373	6.4	0.05488	3.8	0.80	407	20	407	22	407	85	100
a50	5331	189	15	0.71	9913	0.06528	4.4	0.49408	5.5	0.05489	3.3	0.80	408	17	408	19	408	74	100
b39	14431	240	17	0.27	26365	0.06666	2.2	0.51046	4.5	0.05554	3.9	0.49	416	9	419	15	434	87	96
d8	25755	398	28	0.34	29892	0.06665	2.8	0.51232	3.8	0.05575	2.6	0.74	416	11	420	13	442	57	94
c1	10823	161	13	0.68	19834	0.06731	3.5	0.51596	4.0	0.05560	2.0	0.87	420	14	422	14	436	44	96
b22	36912	594	44	0.39	67828	0.06754	4.3	0.51706	5.9	0.05552	4.0	0.74	421	18	423	20	433	88	97
b43	617	10	1	0.45	599	0.06751	3.8	0.88699	12.4	0.09529	11.8	0.30	421	15	645	61	1534	222	27
a59	13789	588	39	0.16	25434	0.06766	4.8	0.51513	6.0	0.05522	3.5	0.80	422	20	422	21	421	79	100
d12	13379	221	16	0.39	24506	0.06766	4.5	0.52096	5.1	0.05584	2.3	0.89	422	18	426	18	446	52	95
b11	10601	126	9	0.40	19354	0.06790	2.6	0.51952	4.1	0.05549	3.2	0.63	423	11	425	14	432	71	98
a20	22106	436	32	0.39	40584	0.06891	3.3	0.52782	3.8	0.05555	2.0	0.86	430	14	430	13	434	44	99
a19	9977	185	14	0.43	18281	0.07007	3.6	0.54069	4.5	0.05597	2.7	0.80	437	15	439	16	451	61	97
a37	8942	179	14	0.47	7871	0.07012	3.4	0.54063	4.7	0.05592	3.2	0.73	437	15	439	17	449	71	97
a10	8503	127	9	0.25	15438	0.07033	3.3	0.54447	3.9	0.05615	2.2	0.84	438	14	441	14	458	48	96
a14	10688	191	14	0.38	19592	0.07023	3.5	0.53900	4.3	0.05566	2.4	0.82	438	15	438	15	439	54	100
d4	24771	387	28	0.30	22295	0.07052	3.4	0.54416	4.6	0.05597	3.0	0.75	439	15	441	17	451	67	97
a22	6940	141	11	0.43	12602	0.07100	3.5	0.55042	6.1	0.05622	4.9	0.58	442	15	445	22	461	109	96
a11	8175	134	10	0.28	14752	0.07111	3.7	0.55212	4.9	0.05631	3.2	0.76	443	16	446	18	465	70	95
b27	28401	430	33	0.40	14515	0.07178	3.9	0.55395	4.4	0.05597	2.1	0.88	447	17	448	16	451	46	99
b16	16855	236	18	0.39	30312	0.07243	3.4	0.56185	4.2	0.05626	2.5	0.81	451	15	453	15	463	55	97
a53	7232	238	20	0.50	1822	0.07377	4.2	0.63509	12.2	0.06244	11.4	0.35	459	19	499	49	689	243	67
b33	14105	235	19	0.50	8039	0.07403	3.6	0.57400	5.9	0.05623	4.7	0.60	460	16	461	22	462	105	100
a32	15457	360	27	0.27	28066	0.07419	3.4	0.57497	3.9	0.05621	1.9	0.87	461	15	461	15	461	42	100
b24	14081	163	13	0.47	9300	0.07436	2.3	0.58027	3.4	0.05660	2.5	0.69	462	10	465	13	476	55	97
b18	11121	171	14	0.36	19698	0.07471	4.2	0.58977	5.2	0.05726	3.0	0.82	464	19	471	20	501	66	93
c4	15969	252	19	0.16	2778	0.07487	3.6	0.58613	4.6	0.05678	2.9	0.78	465	16	468	17	483	64	96
b14	10380	141	11	0.36	18635	0.07588	2.7	0.59076	3.6	0.05647	2.3	0.76	471	12	471	14	471	51	100
a25	26312	453	35	0.30	28811	0.07603	7.4	0.59349	8.9	0.05662	5.0	0.83	472	34	473	34	477	110	99
a57	4447	170	13	0.30	7873	0.07676	4.3	0.60799	6.5	0.05745	4.8	0.67	477	20	482	25	509	106	94
d3	20465	310	23	0.20	36690	0.07701	3.0	0.60701	5.1	0.05717	4.1	0.59	478	14	482	20	498	90	96
a36	12549	310	26	0.50	22497	0.07709	3.3	0.60378	3.8	0.05681	2.0	0.86	479	15	480	15	484	43	99
b28	13514	201	16	0.29	24497	0.07713	3.2	0.60542	4.3	0.05693	2.9	0.73	479	15	481	17	489	65	98
a42	3943	113	10	0.48	7063	0.07813	3.4	0.61363	3.9	0.05696	1.8	0.88	485	16	486	15	490	40	99
a23	7012	124	12	0.55	12530	0.07840	3.6	0.61789	6.1	0.05716	5.0	0.58	487	17	489	24	498	110	98
b29	21129	312	26	0.35	37620	0.07869	4.4	0.61879	5.2	0.05703	2.8	0.85	488	21	489	20	493	61	99
b53	228	4	0	0.19	135	0.07866	3.8	0.89960	34.9	0.08295	34.7	0.11	488	18	652	183	1268	677	38
a45	3440	122	10	0.38	6227	0.07892	3.5	0.61297	4.6	0.05633	2.9	0.77	490	17	485	18	465	64	105
b32	9019	136	13	0.66	5605	0.07899	2.5	0.62454	4.3	0.05734	3.5	0.59	490	12	493	17	505	76	97
a41	4250	112	10	0.55	7757	0.08026	3.4	0.62409	5.4	0.05640	4.2	0.63	498	16	492	21	468	93	106
b19	8463	101	9	0.32	13439	0.08546	2.4	0.69530	3.6	0.05900	2.6	0.69	529	12	536	15	567	57	93
a29	4416	77	7	0.32	7735	0.08568	4.6	0.68706	5.5	0.05816	2.9	0.84	530	23	531	23	536	65	99
a47	5028	155	14	0.55	4440	0.08715	3.9	0.70149	5.3	0.05838	3.6	0.73	539	20	540	22	544	79	99
b35	9014	118	12	0.63	4351	0.08775	1.8	0.70648	4.5	0.05839	4.1	0.41	542	10	543	19	544	89	100
b40	20438	281	28	0.56	35537	0.08765	3.2	0.70541	4.0	0.05837	2.5	0.79	542	16	542	17	544	54	100
b30	16506	184	17	0.26	27820	0.09184	3.1	0.75172	3.7	0.05937	2.0	0.84	566	17	569	16	581	44	98
a33	4767	74	9	0.73	7972	0.10129	4.0	0.85068	5.7	0.06091	4.0	0.71	622	24	625	27	636	87	98
d1	6009	51	6	0.37	10101	0.10170	3.4	0.85786	4.6	0.06118	3.1	0.74	624	20	629	22	646	67	97
b13	31450	268	33	0.20	50044	0.11261	6.0	0.98981	7.2	0.06375	4.1	0.83	688	39	699	37	733	86	94
a18	10380	93	12	0.44	16526	0.11696	4.1	1.03021	4.7	0.06388	2.4	0.86	713	28	719	25	738	51	97
b21	14283	116	14	0.33	17920	0.11773	1.6	1.03809	4.7	0.06395	4.4	0.35	717	11	723	24	740	93	97
b23	12556	91	11	0.27	4710	0.11917	2.8	1.04542	3.6	0.06362	2.2	0.78	726	19	727	19	729	47	100

a56	9053	162	22	0.46	14430	0.11999	5.5	1.06150	7.4	0.06416	4.9	0.75	731	38	735	39	747	104	98
b12	8552	59	11	1.24	6977	0.12009	4.5	1.06850	6.5	0.06453	4.6	0.70	731	31	738	35	759	97	96
b2	15756	93	14	0.61	24510	0.12899	4.8	1.15841	5.4	0.06513	2.3	0.90	782	36	781	30	779	49	100
b36	9116	67	12	0.91	13827	0.13292	3.7	1.22574	4.8	0.06688	3.0	0.78	804	28	812	27	834	62	96
a46	18542	260	37	0.33	28770	0.13300	4.0	1.21017	5.1	0.06599	3.2	0.77	805	30	805	29	806	68	100
b7	10001	47	7	0.39	15175	0.13337	2.9	1.23248	4.0	0.06702	2.8	0.72	807	22	815	23	839	58	96
a38	25092	282	40	0.29	23507	0.13626	3.7	1.24895	4.1	0.06648	1.7	0.90	823	29	823	23	821	36	100
a27	36007	261	40	0.44	512	0.13749	4.1	1.27060	8.5	0.06703	7.4	0.48	830	32	833	49	839	155	99
a24	7875	70	10	0.40	11928	0.14028	3.6	1.30216	4.2	0.06732	2.2	0.86	846	29	847	25	848	46	100
a21	29205	231	34	0.33	43921	0.14131	3.7	1.32286	4.8	0.06790	3.0	0.77	852	29	856	28	865	63	98
b26	55573	353	55	0.44	83483	0.14124	2.7	1.31417	3.2	0.06748	1.8	0.83	852	21	852	19	853	38	100
a1	6179	33	7	1.12	8883	0.15300	3.4	1.49751	4.0	0.07098	2.1	0.84	918	29	929	25	957	44	96
a7	8266	37	7	0.81	11796	0.15456	5.1	1.52638	6.0	0.07162	3.2	0.84	926	44	941	38	975	66	95
b37	40415	268	43	0.30	21301	0.15765	3.8	1.57489	4.4	0.07245	2.2	0.86	944	33	960	28	999	45	95
a9	32654	173	30	0.45	47026	0.15853	3.4	1.54991	3.9	0.07091	1.9	0.87	949	30	950	24	955	38	99
a6	21096	101	19	0.63	29839	0.15876	3.7	1.57960	4.1	0.07216	1.8	0.90	950	33	962	26	991	36	96
b31	79765	428	76	0.44	112030	0.15955	3.8	1.58789	4.9	0.07218	3.1	0.77	954	34	965	31	991	64	96
a30	7001	52	13	1.57	9986	0.16149	3.5	1.59404	4.8	0.07159	3.3	0.73	965	32	968	31	974	68	99
a60	8359	132	20	0.09	6149	0.16249	3.1	1.60905	4.4	0.07182	3.2	0.69	971	28	974	28	981	65	99
a34	34879	432	66	0.06	5849	0.16330	4.7	1.64701	5.3	0.07315	2.6	0.88	975	42	988	34	1018	52	96
a2	104468	618	107	0.33	11909	0.16678	3.9	1.74540	4.8	0.07590	2.7	0.82	994	36	1025	31	1092	55	91
b6	22976	100	19	0.44	30886	0.16802	3.3	1.68216	4.1	0.07261	2.4	0.81	1001	31	1002	27	1003	50	100
d5	38954	171	31	0.36	3626	0.16854	3.0	1.69451	3.7	0.07292	2.3	0.79	1004	28	1006	24	1012	46	99
b10	44446	222	39	0.26	60280	0.16898	1.7	1.74359	3.5	0.07483	3.1	0.47	1007	16	1025	23	1064	63	95
a40	21336	214	37	0.27	29623	0.16995	3.0	1.72087	3.3	0.07344	1.3	0.91	1012	28	1016	21	1026	27	99
b38	19865	84	17	0.65	27801	0.17026	1.6	1.69615	3.7	0.07225	3.3	0.45	1014	15	1007	24	993	67	102
a55	57055	848	143	0.13	13945	0.17083	6.5	1.77232	8.8	0.07524	5.9	0.74	1017	62	1035	59	1075	118	95
b4	24293	118	21	0.27	32739	0.17461	5.9	1.78522	6.9	0.07415	3.6	0.85	1037	57	1040	46	1046	73	99
a44	5124	49	12	1.16	6759	0.17495	4.7	1.86469	5.1	0.07730	1.9	0.92	1039	45	1069	34	1129	39	92
b17	76436	356	60	0.08	57563	0.17656	3.0	1.82790	3.5	0.07509	1.7	0.86	1048	29	1056	23	1071	35	98
a28	81832	567	97	0.06	109701	0.17973	3.4	1.87765	4.5	0.07577	3.0	0.75	1066	33	1073	30	1089	60	98
c2	71217	398	72	0.19	4716	0.18156	3.1	1.95170	13.3	0.07796	12.9	0.23	1076	30	1099	93	1146	256	94
a16	41484	216	44	0.47	52644	0.18455	2.9	2.04743	5.2	0.08046	4.4	0.55	1092	29	1131	36	1208	86	90
a48	15535	146	29	0.25	11676	0.19060	3.8	2.10031	5.3	0.07992	3.7	0.73	1125	40	1149	37	1195	72	94
d7	65941	292	61	0.46	86911	0.19191	2.4	2.05778	3.1	0.07777	2.0	0.78	1132	25	1135	21	1141	39	99
b1	36807	129	26	0.27	46715	0.19236	2.5	2.09797	5.4	0.07910	4.8	0.45	1134	26	1148	38	1175	96	97
a31	60330	472	99	0.39	77591	0.19822	3.1	2.17485	3.5	0.07958	1.7	0.87	1166	33	1173	25	1186	34	98
a3	32497	122	28	0.47	41166	0.20461	3.5	2.26842	3.9	0.08041	1.7	0.90	1200	38	1203	28	1207	34	99
b20	72276	703	137	0.01	6644	0.20703	1.6	2.42291	8.9	0.08488	8.8	0.18	1213	18	1249	66	1313	170	92
a39	34447	208	46	0.25	42863	0.20922	3.8	2.36523	4.3	0.08199	2.0	0.88	1225	42	1232	31	1245	39	98
a5	104195	383	89	0.40	20818	0.21036	4.6	2.37808	4.9	0.08199	1.6	0.95	1231	52	1236	35	1245	31	99
a8	40168	137	34	0.48	48411	0.22342	3.9	2.61042	4.3	0.08474	1.7	0.91	1300	46	1304	32	1310	34	99
c6	100953	277	74	0.40	112644	0.24417	2.7	3.07637	3.0	0.09138	1.4	0.89	1408	34	1427	23	1454	26	97
b25	42053	96	30	0.56	44505	0.26914	2.3	3.55415	3.0	0.09578	2.0	0.76	1536	32	1539	24	1543	37	100
a15	21301	49	15	0.49	22266	0.27602	6.0	3.71575	6.4	0.09763	2.2	0.94	1571	85	1575	53	1579	42	99
d10	67455	140	45	0.60	21523	0.27857	2.1	3.90814	2.5	0.10175	1.3	0.86	1584	30	1615	20	1656	23	96
d11	67124	140	45	0.61	26819	0.27941	2.3	3.92210	2.6	0.10181	1.2	0.88	1588	32	1618	21	1657	23	96
a54	52720	313	102	0.49	53234	0.28302	3.9	3.94019	4.3	0.10097	1.7	0.92	1607	56	1622	35	1642	32	98
a4	97940	201	63	0.31	96102	0.29719	3.3	4.24251	3.6	0.10353	1.4	0.92	1677	49	1682	30	1688	26	99
b34	60089	104	37	0.34	23953	0.32196	3.5	4.95868	4.2	0.11170	2.3	0.84	1799	56	1812	36	1827	41	98
a58	81843	325	127	0.29	68373	0.36264	4.3	6.10709	4.8	0.12214	2.1	0.90	1995	75	1991	43	1988	37	100
a51	99017	296	146	0.56	27901	0.42433	3.4	9.05001	4.3	0.15469	2.5	0.81	2280	66	2343	40	2398	43	95
a35	170185	299	169	0.80	108202	0.44599	4.5	9.86129	4.9	0.16037	2.0	0.91	2377	89	2422	46	2460	35	97
a49	215623	421	222	0.36	136660	0.46354	3.4	10.31402	4.5	0.16138	3.0	0.75	2455	69	2463	43	2470	50	99
b3	280638	165	87	0.36	165754	0.46549	1.7	10.95972	6.6	0.17076	6.4	0.26	2464	36	2520	64	2565	107	96
a13	189127	166	83	0.09	112803	0.47614	3.4	11.22270	3.5	0.17095	1.0	0.96	2510	70	2542	33	2567	17	98
a52	61345	113	61	0.28	35983	0.48023	4.2	11.52951	5.6	0.17413	3.7	0.76	2528	89	2567	54	2598	61	97
b8	110427	68	42	0.54	63532	0.49850	3.0	12.13716	3.4	0.17658	1.6	0.88	2607	64	2615	32	2621	26	99

[a]within-run background-corrected mean ^{207}Pb signal in counts per second; [b]U and Pb content and Th/U ratio were calculated relative to GJ-1 and are accurate to approximately 10%; [c]corrected for background, mass bias, laser induced U-Pb fractionation and common Pb (if detectable, see analytical method) using Stacey & Kramers (1975) model Pb composition. $^{207}Pb/^{235}U$ calculated using $^{207}Pb/^{206}Pb/(^{238}U/^{206}Pb \times 1/137.88)$. Errors are propagated by quadratic addition of within-run errors (2SE) and the reproducibility of GJ-1 (2SD); [d]Rho is the error correlation defined as $err^{206}Pb/^{238}U/err^{207}Pb/^{235}$

Table 3. Age ranges and percentage of detrital zircons in the samples VN23 (Van Huong Formation) and VN24 (Van Canh Formation). The ^{207}Pb/^{206}Pb age was taken for interpretation for all zircons >1.0 Ga, and the ^{206}Pb/^{238}U ages for younger grains. The applied stratigraphic time scale is based on data published in Ogg et al. (2016)

	Range(Ma)	VN23 (%)	VN24 (%)
Lower Devonian	393-419	4.6	4.7
Silurian	419-444	12	11.3
Ordovician	444-485	28.9	12.3
Cambrian	485-541	7.4	8.5
Neoproterozoic	541-1000	19.4	28.2
Mesoproterozoic	1000-1600	17.6	24.5
Palaeoproterozoic	1600-2500	7.4	7.5
Archaean	2500-4000	2.7	2.8

Concordia plots and concordia age of the youngest zircon population of detrital zircons of sample VN23 and VN24 are displayed in Figures 6 and 7. All analysis of the zircons are concordant with a range from the Archean (~2500 Ma) to Palaeozoic (~400 Ma) in both samples. The age distribution of zircon grains in sample VN24 from the Van Canh Formation is more complex with multiple age peaks compared to those in sample VN23 from the Van Huong Formation. The largest group of zircons in sample VN24 belong to the Palaeozoic age, ranging from 541 Ma to 393 Ma (36,8%, Table 1). The main peaks in the probability plot occur at 437 Ma and 476 Ma, which are flanked by a minor peak at 537 Ma.

Neoproterozoic zircons with age ranging from 541 Ma to 1000 Ma represent the second largest group with 28.2%, followed by Mesoproterozoic zircons with age ranging from 1000 Ma to 1600 Ma (24.5%). The main peaks of Neoproterozoic zircon grains lie at ~720 Ma and ~810 Ma. A large peak of Mesoproterozoic zircon grains is found at ~1020 Ma. 7.5% of the zircon population from sample VN24 show a Palaeoproterozoic age (Table 3) with distinct peaks at ~1580 Ma and 2450 Ma (Figure 8). A few zircons (2.8%) yield the Archaean age (Table 3).

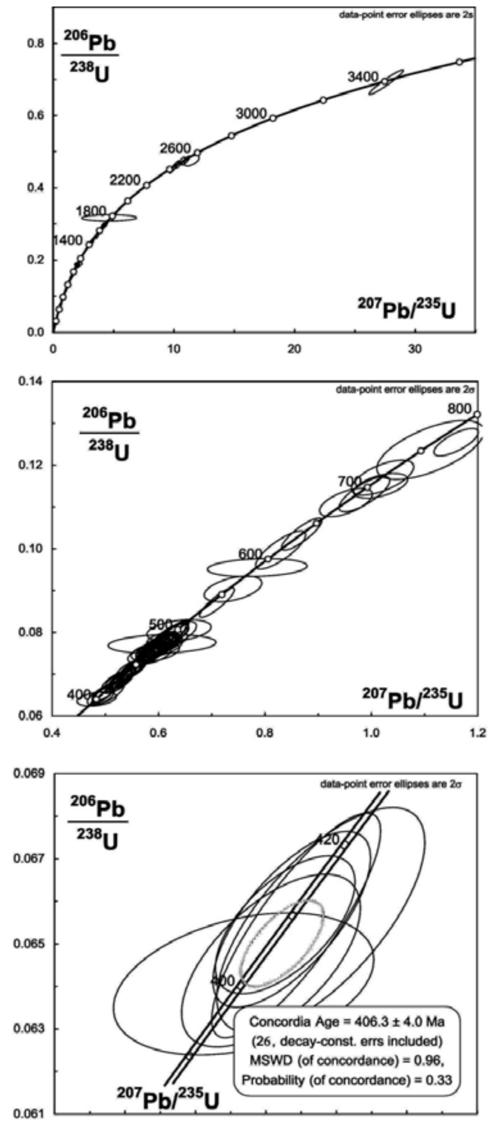

Figure 6. Concordia plots and concordia age of the youngest zircon population of detrital zircon of sample VN23

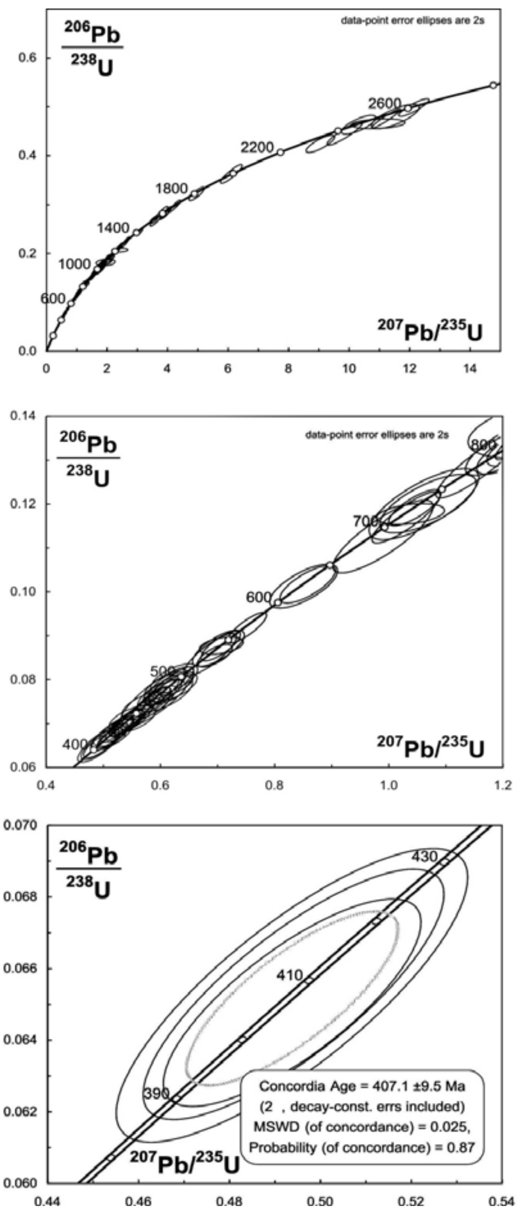

Figure 7. Concordia plots and concordia age of the youngest zircon population of detrital zircon of sample VN24

The age spectrum of zircon grains in sample VN23 from the Van Huong Formation is comparable to that of sample VN24, but also exhibits some differences. The sample shows a large number of Palaeozoic zircon grains (53%, Table 3) with a concentration of Ordovician grains (28.9 %) and a pronounced peak at ~475 Ma. Neoproterozoic zircons are represented by 19.4% of all measured grains, in contrast to 28.2% in sample VN24 from the Van Canh Formation. Generally, Neoproterozoic zircon grains are evenly distributed (Table 3), but show a larger peak at ~963 Ma. The number of Mesoproterozoic zircon grains in sample VN23 (17.6%) also differs from that of sample VN24 (24.5%). Mesoproterozoic zircons exhibit a peak at ~1087 Ma but this peak is less prominent in comparison to that at ~1020 Ma in the sample VN24 (Figures 8, 9). The percentage distribution of zircon grains with Palaeoproterozoic and Archean ages of both samples are quite similar, having a peak at ~2500 Ma, but sample VN23 exhibits a major gap in age in the Palaeoproterozoic (Figure 9).

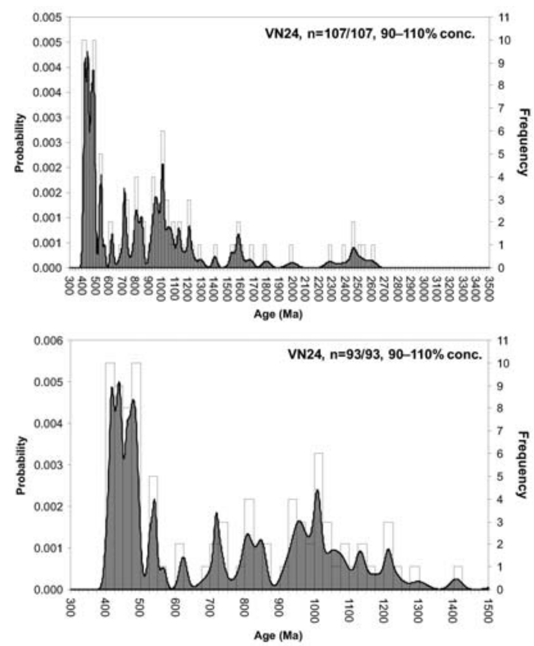

Figure 8. Probability diagram of U-Pb ages of detrital zircons from sample VN24 (Silurian(?) to Early Devonian Van Canh Formation)

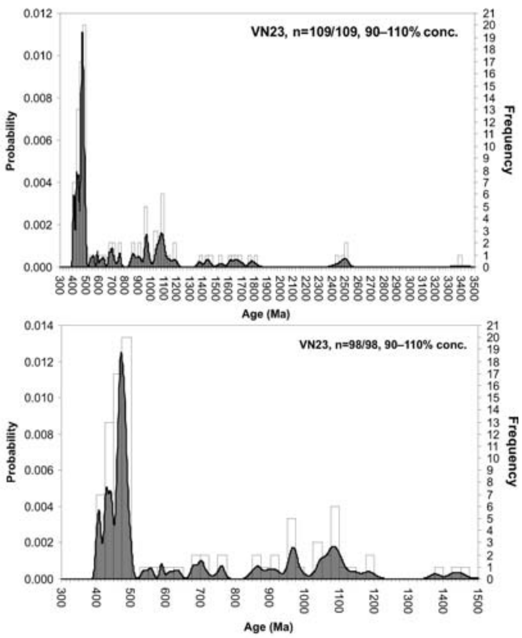

Figure 9. Probability diagram of U-Pb ages of detrital zircons from sample VN23 (Middle Devonian Van Huong Formation)

5. Discussion

U-Pb ages of detrital zircons from the investigated Van Canh Formation (sample VN24) of the Do Son Peninsula reflect two main episodes of crustal recycling, at ~407-480 Ma and ~940-1100 Ma, with minor peaks at ~537 Ma, ~720 Ma, ~812 Ma, ~1600 Ma, and ~2500 Ma (Figure 5). In northwestern Vietnam detrital zircon U-Pb ages from rocks of the Sin Quyen Formation exhibit major age peaks in the Neoarchean (2.7-2.0 Ga and 2.2-2.5 Ga.) as well as in the Palaeoproterozoic (~1.8 Ga.; Hieu et al., 2012, see also Mydung et al., 2014). Similar zircon age patterns from rocks of the Ca Vinh Complex are published in Nam et al. (2003). Palaeoproterozoic zircon ages are known from the Phan Si Pan Zone in northern Vietnam. Anh et al. (2015) report U-Pb ages for the Deo Khe Granitoids ranging from 1855-1873 Ma, which are similar to zircon ages of 1.85 Ga reported from the Yangze Block in South China (Zhao and Cawood, 2012).

Intrusive bodies which indicate the existence of a Caledonian tectonothermal event in Vietnam are widely distributed. Based on geochronological U-Pb and ^{40}Ar-^{39}Ar data published by Nagy et al. (2001) and Vu Van Tich (2001), this event was recognized in the Kontum Massif in central Vietnam, were magmatic rocks exhibit U-Pb ages ranging from 450 Ma to 424 Ma. Recently, Hieu et al. (2016) published zircon age dates of ~430 Ma from the Dai Loc granitoid complex, Kontum Massif. Middle Palaeozoic U-Pb ages of intrusive rocks are also reported from the Thien Ke granite pluton in the Tam Dao region (Nguyen et al., 2014) and the Song Chay area (Roger et al., 2000; Yan et al., 2006).

Relative probability plots for zircon ages of the Van Canh Formation (sample VN24, Figure 8) are similar to those from samples collected from the NE Vietnam Terrane which have major peaks at ~440 Ma, ~944 Ma and ~980 Ma and a minor peak at ~2400 Ma, as well as samples from the Ailaoshan Terrane, in southern China (Burrett et al., 2014; see Figure 10). According to these authors, the zircon peak of 800 Ma (Sibao orogeny) is weakly developed in NE Vietnam. This peak was less prominent in the sample of the Van Canh Formation (sample VN24; Figures 8, 10) and is absent in the overlying Van Huong Formation (sample VN23), as shown in Figures 8-10, thus confirming the results published of Burrett et al. (2014). In South Cathaysia, detrital zircons exhibit a wide age spectrum, but it is important to note that they also cluster in two age peaks, at ~970 Ma and at ~2500 Ma (Yu et al., 2009) which is similar to the zircon spectrum presented in our study.

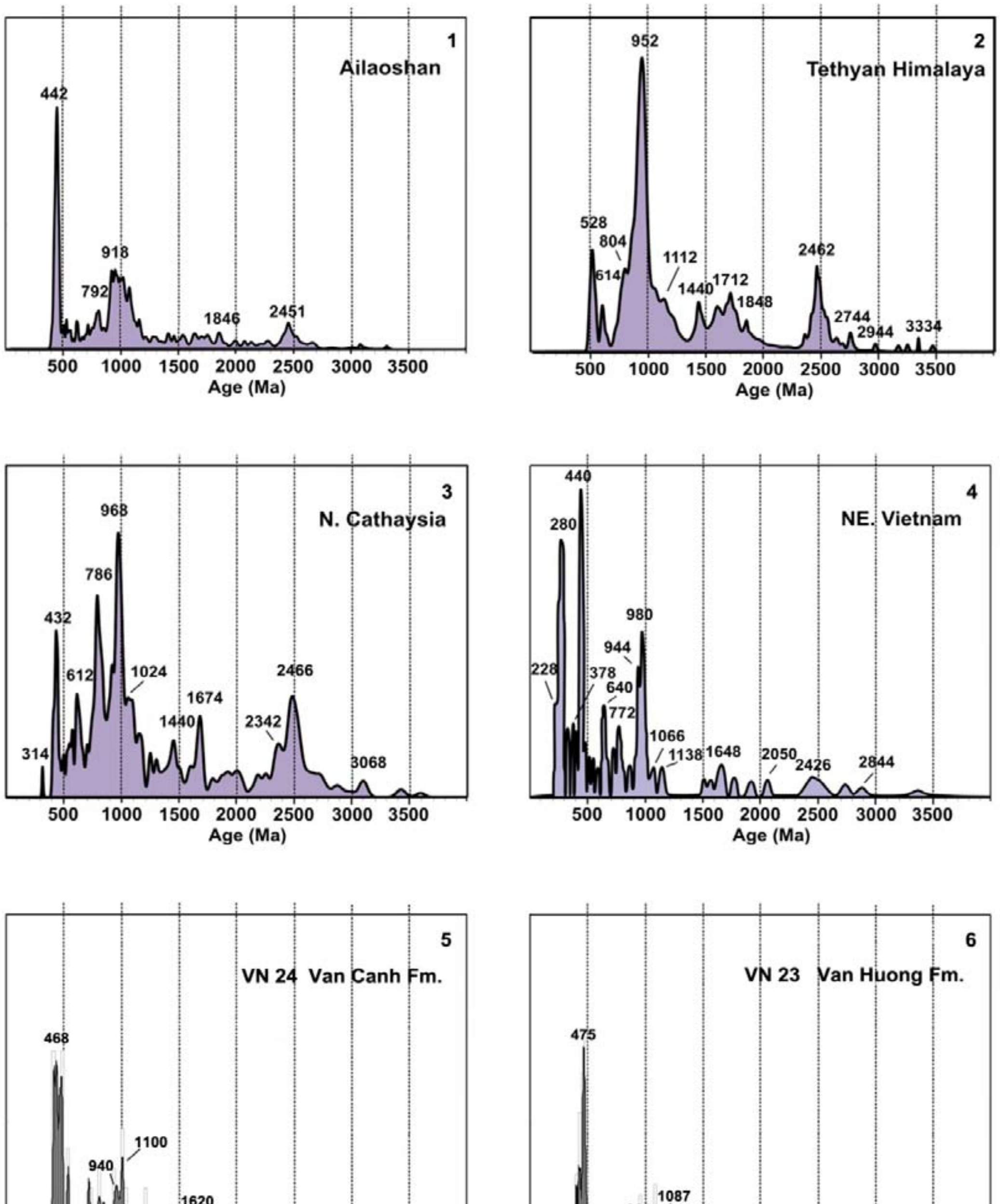

Figure 10. Relative probability plots of terranes and areas discussed in this study: Number (1) Ailaoshan Terrane (southern China), (2) Tethyan Himalaya, (3) Cathaysia Terrane (4) NE Vietnam from Burrett et al. (2014), (5) Van Canh Formation, Do Son Peninsula, Vietnam (this study), (6) Van Huong Formation, Do Son Peninsula, Vietnam (this study)

Zhu et al. (2011) reported that the presence or absence of younger (~950 Ma) or older Grenvillian (~1170 Ma) detrital zircons can be used to discriminate whether the blocks are derived from Indian or Australian margins. Whereas the younger Grenvillian zircons originated from the Tethyan Himalaya, the older Grenvillian zircons are derived from the Albany-Fraser belt in southwestern Australia (Zhu et al., 2011). The presence of younger Grenvillian zircons in the Van Canh Formation (VN24) supports the postulated position of NE Vietnam close to the western Himalaya. A few 2280-2377 Ma zircon grains are characterized by pale rims depleted in uranium, which were derived from rocks that underwent high pressure metamorphic conditions. Himalayan Palaeoproterozoic rocks could be the source area and angular to-well-rounded zircons in our samples suggest at least moderate transport distances.

U-Pb ages of detrital zircons from the Middle Devonian Van Huong Formation show a major peak at ~406-475 Ma and smaller peaks at ~963 Ma, ~1087 Ma, and a small Palaeoproterozoic input at ~2500 Ma. The latter peak is also known from sample VN24 (Figures 8, 9). A possible source for this zircon peak may be associated with the Wutai orogeny, an event that is also known in the Tethyan Himalaya, Cathaysia, India, and Africa (Yu et al., 2009; Condie et al., 2009; Wan et al., 2011; Burrett et al., 2014).

According to Squire et al. (2006), the denudation of highlands that were formed during the Pan African and older orogenies were responsible for the detrital sediment transport across Gondwana. The age spectrum of zircon grains in sample VN24 (Lower Devonian Van Canh Formation) exhibits Neoproterozoic, Mesoproterozoic, and Palaeoproterozoic zircon grains whereas the overlying sample VN23 (Middle Devonian Van Huong Formation) shows a major gap in the Palaeoproterozoic record (Figures 9, 10). This might be a result of reduced denudation, changing fluvial flow directions and/or slightly changing palaeogeographic position of northeast Vietnam.

The youngest zircon of each formation provides maximum ages of sedimentation at 407.1 ± 9.5 Ma and 406.3 ± 4.0 Ma, which are in general agreement with the palaeontological data from the Middle Devonian Van Huong and the Early Devonian Van Canh Formations. Facies development and faunal similarities can also provide constraints on the palaeogeographic position of NE Vietnam. According to Xun et al. (1996), Lower Devonian sediments adjacent to the Huanan Landmass are characterized by a wide range of shallow-water to alluvial facies settings. Similar facies settings are known from northeast Vietnam. The assumed palaeogeographic position of NE Vietnam in the Early and Middle Devonian close to the western Himalayas is most likely due to faunal similarities between Vietnam and southern China (Janvier and Ta Hoa, 1999; Janvier and Tong-Dzuy, 1988; Jones et al. 1997). Based on vertebrates, ostracods, and brachiopods there is likely a palaeobiogeographic relation between the East Red River region in Vietnam and southern China. Racheboeuf et al. (2005) describe beyrichiids and leperditids from NE Vietnam (Ha Giang Province) which closely resembles forms from the Silurian and Devonian of the Yunnan Province of South China. Furthermore, the vertebrate fauna of NE Vietnam and South China is also similar (Janvier and Ta Hoa, 1999). The Silurian part of the Do Son Group (lower part of the Van Canh Formation) on the Do Son Island contains fish remains which can be related to primitive antiarchs that are morphologically close to species reported from the Late Silurian and Early Devonian in China (Janvier and Tong-Dzuy, 1988). The overlying Middle Devonian Van Huong Formation of the section shows comparable faunal elements and exhibits similar fluviodeltaic facies settings comparable to Givetian to Late

Devonian sediments along the southeastern coast of China (Long et al., 1990; Lee, 1991; Jones et al., 1997).

6. Conclusions

Detrital zircons from two Devonian siliciclastic rocks, the Van Canh and the Van Huong Formations from the Do Son Peninsular (NE Vietnam) were analyzed for U, Th, and Pb isotopes by LA-SF ICP-MS techniques. The youngest zircon of each formation exhibits maximum ages of sedimentation at 407.1±9.5 Ma (Van Canh Formation) and 406.3±4.0 Ma (Van Huong Formation) which confirms published biostratigraphic age data. The zircon cluster of both samples from the east Red River Basin as well as palaeontological affinities to South China, confirms reconstructions for NE Vietnam close to the western Himalayas suggested by earlier studies.

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