Determining Precambrian crustal evolution in China: a case-study from Wutaishan, Shanxi Province, demonstrating the application of precise SHRIMP U–Pb geochronology

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Abstract: SHRIMP U–Pb zircon analyses from eight samples of metamorphosed intermediate to felsic volcanic rocks from the lower, middle and upper 'subgroups' of the Wutai sequence in the North China Craton define a weighted mean $^{207}Pb/^{206}Pb$ age of 2523 ± 3 Ma. Although individual rock ages range from 2533 ± 8 Ma to 2513 ± 8 Ma, all overlap within the error of the mean and do not support a stratigraphic interpretation for the sequence, since variations within individual previously assigned 'formations' in the sequence match the total age range. Contrary to previous interpretations, there is no correlation in age with metamorphic grade. These features highlight the need to reformulate stratigraphic schemes when defining the Precambrian geology of the North China Craton. The similarity in age between volcanic rocks of the Wutai Complex and higher-grade gneisses of the adjacent Fuping and Hengshan complexes supports the view that all three complexes represent portions of a Late Archaean arc complex that was tectonically dismembered and then re-assembled. There is no Fuping or Wutai orogeny in this, its type area: all three complexes were deformed and metamorphosed during collision of the eastern and western blocks of the North China Craton in the Lüliang orogeny *c.*1.8 Ga ago.

As elsewhere, Chinese geology grew up on the tradition of stratigraphy. However, these techniques have their limitations, as evidenced by major advances in both structural geology and tectonics in the 1960s. These techniques are only now being applied in China, and many older geological interpretations need to be revised. As examples, we can note the application of stratigraphic terms such as 'group' and 'formation' to non-sedimentary rocks – including high-grade gneisses – and the previous widely-held view that the higher the metamorphic grade or degree of structural complexity, the older the rock. Similarly, the late recognition of the nature and significance of ductile shear zones means that many stratigraphic relationships now need to be reinvestigated, in particular, key 'unconformities'. When this is coupled with a local terminology related to tectonic events such as 'movements', 'uplifts' and 'tectonic stages/cycles' – which predate the acceptance of plate-tectonic theory – we can see some of the reasons for confusion and possible misinterpretation.

We demonstrate here, through the use of precise, high-resolution, single-zircon geochronology, that the traditionally accepted interpretation of the geology in the Wutaishan area, located approximately 200 km west-southwest of Beijing in the Central Zone (Fig. 1) of the North China Craton (Zhao *et al.* 2001*b*), requires significant modification. The study area was selected because the traditional Chinese view (Bai 1986; Tian 1991; Tian *et al.* 1996) is that the Precambrian succession here is essentially a stratigraphic sequence that can be subdivided on the basis of orogenic 'movements'; and the type areas of two of these – the Fuping and Wutai 'movements' – are located in this region (Fig. 2). Instead, our results will establish that we are dealing with a lithotectonic package that has been assembled during a major collisional event in the Palaeoproterozoic.

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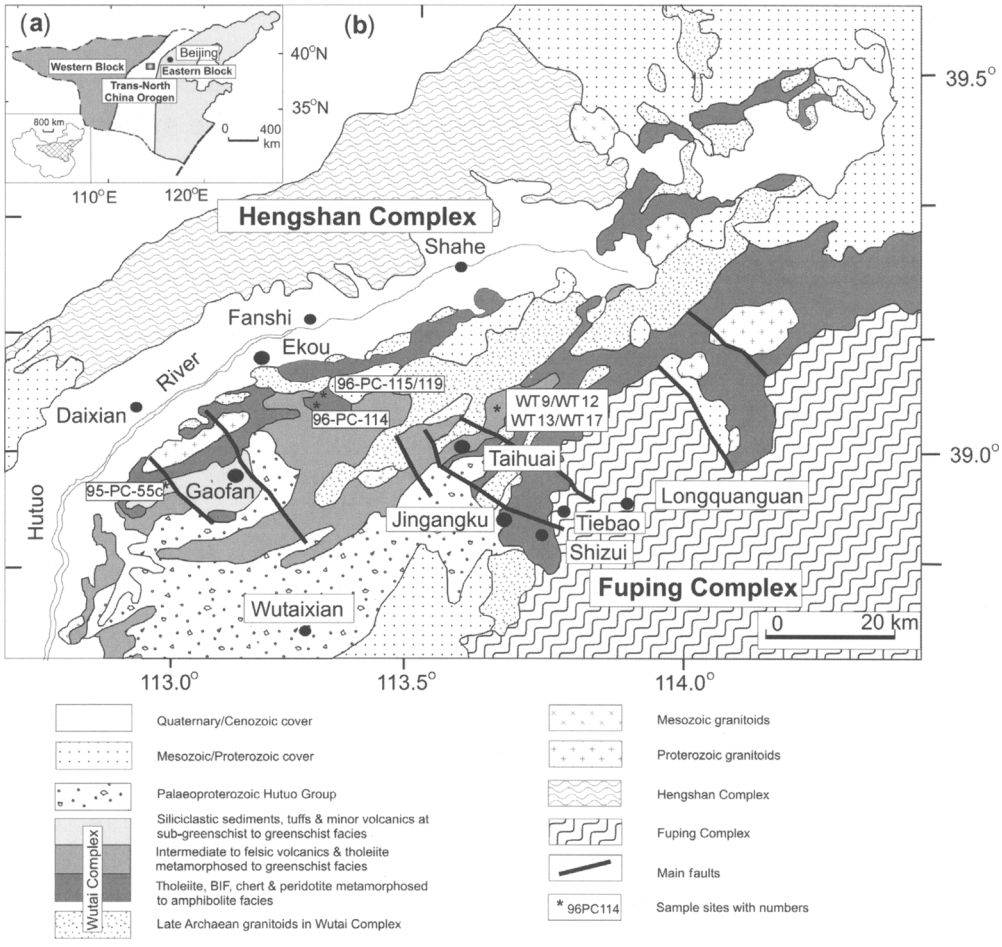

Fig. 1. (**a**) Map showing the three-fold subdivision of the North China Craton into the Trans-North China Orogen and Eastern and Western blocks (study area shown as a small rectangle southwest of Beijing); inset shows the location of North China Craton within China. (**b**) Simplified geological map of the Wutai–Hengshan–Fuping area, showing sample locations (modified from Sun *et al.* 1992 and Zhao *et al.* 2001*b*).

Previous work

The Precambrian rocks in the Wutaishan area (Fig. 2) are considered in the Chinese literature to represent three main 'cycles' (see Bai 1986; Tian *et al.* 1996), characterized by discrete events of sedimentation, granitoid intrusion, metamorphism and deformation, and separated by two major orogenic episodes or 'movements'. The older Fuping 'cycle' extended from 2.9 to 2.5 Ga, and consisted of volcanogenic sediments (Hengshan and Fuping 'groups'), which were metamorphosed to upper amphibolite–granulite facies prior to intrusion of extensive bodies of tonalite–trondhjemite–granodiorite (TTG) and mafic dykes. The entire package was then deformed and metamorphosed to upper amphibolite–granulite facies at *c.*2.5 Ga and underwent local partial melting. This event is referred to as the Fuping 'movement' and considered to represent the culmination of a tectonic 'stage'. The succeeding Wutai 'cycle' of volcanic rocks and volcanogenic sediments was deposited on the deformed Fuping 'Group' between 2.5 and 2.4 Ga, and variably metamorphosed between 2.3 and 2.2 Ga, with the lower rocks attaining amphibolite facies and the upper rocks only sub-greenschist facies metamorphism; this likewise is considered to be the termination of a tectonic 'stage', and the event is referred to as the Wutai 'movement'. Rocks of the Wutai 'Group' have been considered to

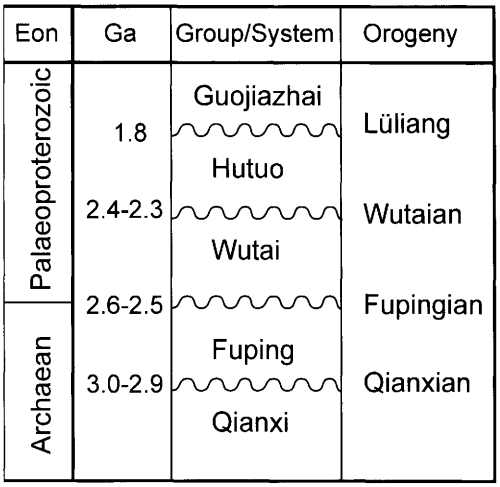

Fig. 2. Major subdivisions of the Precambrian of China, using the traditional breakdown into 'groups' ('cycles') and orogenies (or 'movements') (based on Ma & Bai 1998).

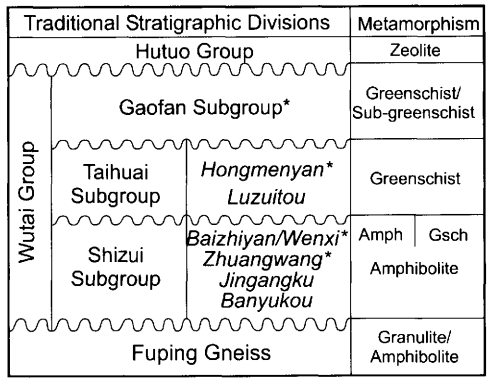

Fig. 3. Traditional subdivision of the Wutai 'Group' of Shanxi province, based on Tian (1991) and Ma & Bai (1998). The asterisks refer to 'formations' dated in this study.

have typical Archaean greenstone belt affinities (Bai 1986). Finally, the Hutuo 'Group', a sequence of shallow-water carbonates and siliciclastic sedimentary rocks, was deposited over the deformed and metamorphosed Wutai and Fuping 'groups', between 2.3 and 2.0 Ga, and metamorphosed at 2.0 to 1.8 Ga. This constitutes the Lüliang 'cycle', and the peak metamorphic event was considered to be between 1.85 and 1.7 Ga, and is referred to as the Lüliang 'movement'.

This sequence of events is considered to be typical for China and is applied to areas not just within the North China Craton, but to the South China and Tarim cratons as well (see Ma & Bai 1998).

The rocks at Wutaishan have traditionally been considered to form a complete stratigraphic succession – known as the Wutai 'Group' – composed of a lower sequence of amphibolite, banded iron formation, paragneiss and minor carbonate, that was metamorphosed to amphibolite facies. These are overlain by middle and upper sequences composed of clastic sedimentary rocks and intermediate to felsic volcanic rocks, that have been metamorphosed to greenschist or sub-greenschist facies. Thus the older rocks are considered to be of higher metamorphic grade. The rocks have been further subdivided into a number of 'formations' (Fig. 3), locally separated by 'unconformities' (Tian *et al.* 1996), and represent one of the classical stratigraphic sequences in the Chinese Precambrian (Bai 1986). Although a modern plate-tectonic interpretation has recently been applied to the rock association (Ma & Bai 1998), it is still considered to maintain a coherent stratigraphy.

Based on preliminary results, we have shown that this interpretation is inadequate on several grounds, including:

(1) the apparent similarity in age of volcanic rocks throughout the Wutai sequence (Wilde & Wang 2000);
(2) many of the so-called 'unconformities' being tectonic contacts (Cawood *et al.* 1998); and,
(3) the provenance age of zircons within the metasedimentary units indicate that the basal sequence of the Wutai Complex is younger than the overlying volcanic rocks (Cawood *et al.* 1998).

In view of these findings, we refer here to the rocks as belonging to the Wutai Complex (Wilde *et al.* 1997). All previous stratigraphic terms will be marked within parentheses.

Prior to commencement of our work in the area in 1995, the traditional view, as outlined above (Figs 2 and 3), was being questioned, and controversy surrounded the nature and age of the rocks at Wutaishan. They were variously considered to be Archaean in age (Wang & Bai 1986), or else marked the base of the Proterozoic in China (Yang *et al.* 1986). Liu *et al.* (1985) provided a broad geochronological framework for the area, using conventional multigrain U–Pb zircon techniques. They dated what was referred to as a low-grade keratophyre lava in the central part of the Wutai sequence (Hongmenyan Formation of Li S. *et al.* 1990; see Table 1) just north of Taihuai (Fig. 1), obtaining an age of 2520 ± 17 Ma. However, Wang & Bai (1986)

considered these rocks to be part of a granitic intrusion, implying that it may be younger than the volcanic succession. Subsequent Rb–Sr, Pb/Pb and Sm–Nd isotopic analyses yielded significantly younger ages for this sequence. A combined Sm–Nd isochron age of *c.*2250 Ma from samples of the so-called spilite–keratophyre sequence near Taihuai was interpreted as an 'errorchron', resulting from mobilization of REE during low-grade metamorphism (Li S. *et al.* 1990). Separate isochrons from these spilite and quartz–keratophyre samples yielded ages of around 1980 Ma, within the error of the Rb–Sr isochron age (Li S. *et al.* 1990). A later Rb–Sr, Pb/Pb and Sm–Nd study by Sun *et al.* (1992) on mafic rocks from Wutaishan yielded similar dates. These post-Archaean ages have tended to be interpreted as primary ages (see Tian *et al.* 1996), rather than the more robust U–Pb zircon dates of Liu *et al.* (1985).

A SHRIMP $^{207}Pb/^{206}Pb$ date of 2524 ± 8 Ma for a rhyodacitic lava from the Hongmenyan 'Formation' within the 'middle' Wutai clearly confirms its Archaean age (Wilde *et al.* 1997).

The minimum age of the Wutai Complex is constrained by the age of the overlying Hutuo 'Group' and that of the intrusive, essentially post-tectonic Dawaliang Granite. Conventional multigrain U–Pb zircon analyses from a Hutuo 'Group' metabasalt gave a date of 2366 +103/−94 Ma (Wu *et al.* 1986), which was considered to be the age of igneous crystallization. Sun *et al.* (1992) later argued that it could be a metamorphic age. The Dawaliang Granite has a SHRIMP $^{207}Pb/^{206}Pb$ date of 2176 ± 12 Ma (Wilde *et al.* 1997), interpreted as the igneous crystallization age.

In this paper, we will present new data on the ages of felsic volcanic rocks within the regional 'stratigraphy' (confirmed by Yongqing Tian, pers. comm.). The results are discussed in relation to recent evidence on the nature of adjacent terrains and the implications that these have for the Late Archaean to Palaeoproterozoic evolution of the North China Craton.

Timing of felsic volcanism within the Wutai Complex

We collected a suite of eight metamorphosed intermediate to felsic volcanic rocks from four units previously recognized as 'formations', including samples from what were considered to be the lower, middle and upper 'subgroups' (Fig. 3). These are described below in their previously assumed stratigraphic order, using the traditional formational names (e.g. Bai 1986; Tian 1991). The Hongmenyan 'Formation' is considered to have the best-developed sequence of intermediate to felsic volcanic rocks, and we selected four samples from this unit for analysis from the well-exposed roadside section on Wutai Mountain, approximately 15 km by road north-northeast of Taihuai (Fig. 1). All coordinates quoted in this paper were collected with a hand-held Trimble or Garmin GPS.

Sample descriptions

All rocks in the Wutai Complex are strongly deformed and have undergone either greenschist- or amphibolite-facies metamorphism. The samples selected for analysis are fine-grained, meso- to leucocratic schistose rocks, composed of variable amounts of quartz, feldspar, biotite, muscovite and hornblende, with minor epidote, chlorite, magnetite, pyrite and calcite. Geochemical data for these rocks (Wilde, unpublished data; Wang *et al.* in press) and the local preservation of igneous textures establish their volcanic parentage and, in the following sections, we use their volcanic names for brevity.

Zhuangwang 'Formation'. Sample 96-PC-114 was obtained from an exposure along the side road leading to the Ekou Iron Mine, *c.*20 m on the uphill side of a short tunnel (Fig. 1). The rock is a fine-grained mesocratic andesite. It has a well-developed metamorphic fabric defined by strongly aligned biotite laths, with local development of poikiloblastic blue-green amphibole. The remainder is composed of an aggregate of weakly aligned quartz and untwinned feldspar, with granular epidote and aligned laths of chlorite. Pyrite is a common accessory mineral. There are a few calcite veins, and the whole rock has a crenulated fabric. It has been metamorphosed to the epidote amphibolite facies.

The zircons are colourless to pale pink and mostly euhedral with well-formed prismatic and pyramidal faces. The length to width ratio ranges from 2:1 to 3.5:1. Some crystals contain rounded titanite or elongate apatite inclusions. A number of grains are fractured and metamict.

Sample 96-PC-119 was obtained from a roadside exposure on the Ekou–Yantou road, *c.*100 m north of the turn-off to the Ekou Iron Mine. The rock is a buff-grey mesocratic andesite with a micaceous foliation that is interbanded with garnet–mica schist. It consists of a granoblastic aggregate of quartz and untwinned feldspar (mostly plagioclase), interspersed with strongly aligned biotite and muscovite. The mica laths locally show tight to isoclinal folding, with

Table 1. *SHRIMP U–Pb–Th zircon data for Wutai Volcanic samples 96-PC-114, 96-PC-119 and 96-PC-115*

Spot	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	$^{204}Pb/^{206}Pb$	% f^{206a}	$^{208}Pb^*/^{206}Pb^*$	$^{208}Pb^*/^{232}Th$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$	% conc.	Age $^{207}Pb^*/^{206}Pb^*$
Sample 96-PC-114													
pc114-1	46	24	0.51	25	0.00069	1.108	0.1408 ± 69	0.1303 ± 75	0.4721 ± 129	10.86 ± 39	0.16691 ± 345	99	2527 ± 35
pc114-2	113	81	0.72	61	0.00020	0.323	0.2018 ± 34	0.1271 ± 40	0.4545 ± 114	10.45 ± 30	0.16674 ± 177	96	2525 ± 18
pc114-3	73	69	0.95	43	0.00075	1.205	0.2540 ± 62	0.1248 ± 46	0.4652 ± 121	10.90 ± 36	0.16989 ± 296	96	2557 ± 29
pc114-4	52	31	0.59	28	0.00063	1.011	0.1701 ± 67	0.1309 ± 64	0.4518 ± 122	10.53 ± 37	0.16907 ± 330	94	2548 ± 33
pc114-5	34	42	1.23	23	0.00107	1.707	0.3377 ± 98	0.1349 ± 58	0.4930 ± 142	12.32 ± 49	0.18126 ± 448	97	2664 ± 41
pc114-6	64	43	0.66	37	0.00082	1.318	0.1815 ± 60	0.1292 ± 56	0.4727 ± 125	10.96 ± 37	0.16817 ± 297	98	2539 ± 30
pc114-7	50	43	0.87	28	0.00059	0.945	0.2447 ± 69	0.1288 ± 52	0.4578 ± 125	10.25 ± 37	0.16238 ± 326	98	2481 ± 34
pc114-8	186	163	0.88	90	0.00028	0.455	0.2656 ± 27	0.1159 ± 31	0.3828 ± 94	10.07 ± 27	0.19084 ± 143	76	2749 ± 12
pc114-9	136	130	0.96	66	0.00186	2.978	0.2771 ± 67	0.1037 ± 37	0.3581 ± 90	8.40 ± 27	0.17015 ± 305	77	2559 ± 30
pc114-10	62	31	0.49	35	0.00067	1.065	0.1331 ± 52	0.1311 ± 62	0.4874 ± 127	11.05 ± 36	0.16449 ± 263	102	2502 ± 27
pc114-11	118	76	0.65	67	0.00033	0.522	0.1792 ± 30	0.1338 ± 41	0.4833 ± 120	11.16 ± 31	0.16749 ± 158	100	2533 ± 16
pc114-12	157	127	0.81	90	0.00026	0.413	0.2229 ± 24	0.1303 ± 36	0.4742 ± 116	11.11 ± 29	0.16986 ± 128	98	2556 ± 13
pc114-13	79	35	0.44	44	0.00053	0.842	0.1241 ± 41	0.1356 ± 58	0.4841 ± 123	11.17 ± 33	0.16728 ± 216	101	2531 ± 22
pc114-14	95	66	0.70	55	0.00035	0.557	0.1969 ± 34	0.1356 ± 43	0.4809 ± 121	11.10 ± 32	0.16734 ± 178	100	2531 ± 18
pc114-15	76	44	0.57	43	0.00032	0.511	0.1586 ± 39	0.1339 ± 49	0.4848 ± 124	11.23 ± 33	0.16799 ± 204	100	2538 ± 20
pc114-16	67	52	0.78	40	0.00060	0.957	0.2126 ± 45	0.1348 ± 46	0.4951 ± 127	11.42 ± 35	0.16735 ± 224	102	2531 ± 22
pc114-17	41	22	0.55	24	0.00113	1.810	0.1422 ± 75	0.1268 ± 76	0.4874 ± 132	11.02 ± 41	0.16399 ± 364	102	2497 ± 37
pc114-18	146	148	1.02	87	0.00024	0.389	0.2820 ± 26	0.1308 ± 35	0.4727 ± 116	10.80 ± 29	0.16576 ± 130	99	2515 ± 13
pc114-19	47	29	0.61	27	0.00049	0.778	0.1740 ± 61	0.1394 ± 64	0.4912 ± 132	11.37 ± 39	0.16789 ± 306	102	2537 ± 31
pc114-20	75	78	1.04	46	0.00041	0.650	0.2898 ± 44	0.1343 ± 41	0.4822 ± 123	11.10 ± 33	0.16689 ± 211	100	2527 ± 21
pc114-21	86	89	1.04	53	0.00045	0.724	0.2896 ± 48	0.1351 ± 42	0.4835 ± 123	11.28 ± 34	0.16919 ± 225	100	2550 ± 22
pc114-22	63	52	0.83	38	0.00044	0.706	0.2318 ± 45	0.1357 ± 46	0.4877 ± 126	11.23 ± 34	0.16694 ± 226	101	2527 ± 23
pc114-23	92	27	0.30	52	0.00055	0.887	0.0770 ± 36	0.1316 ± 71	0.5068 ± 128	12.80 ± 37	0.18322 ± 202	99	2682 ± 18
pc114-24	88	62	0.70	50	0.00071	1.142	0.1876 ± 47	0.1261 ± 46	0.4708 ± 120	10.48 ± 32	0.16149 ± 229	101	2471 ± 24
pc114-25	35	19	0.53	21	0.00113	1.811	0.1440 ± 87	0.1326 ± 90	0.4907 ± 140	11.00 ± 45	0.16265 ± 420	104	2483 ± 44
Sample 96-PC-119													
96pc119-1	240	113	0.47	108	0.00011	0.182	0.1010 ± 10	0.0878 ± 11	0.4077 ± 23	9.36 ± 7	0.16657 ± 66	87	2523 ± 7
96pc119-2	238	166	0.70	127	0.00011	0.177	0.1980 ± 12	0.1283 ± 12	0.4521 ± 26	10.35 ± 7	0.16607 ± 64	95	2518 ± 7
96pc119-3	258	401	1.56	168	0.00008	0.125	0.4340 ± 15	0.1312 ± 10	0.4704 ± 26	10.78 ± 7	0.16618 ± 59	99	2519 ± 6
96pc119-4	47	16	0.34	26	0.00027	0.431	0.0924 ± 34	0.1339 ± 52	0.4938 ± 55	11.28 ± 19	0.16571 ± 181	103	2515 ± 18
96pc119-5	205	199	0.97	119	0.00004	0.062	0.2693 ± 13	0.1295 ± 11	0.4652 ± 28	10.77 ± 8	0.16798 ± 63	97	2538 ± 6
96pc119-6	331	164	0.50	162	0.00007	0.104	0.1400 ± 9	0.1233 ± 11	0.4362 ± 23	9.91 ± 6	0.16473 ± 53	93	2505 ± 5
96pc119-7	683	289	0.42	275	0.00005	0.074	0.1143 ± 6	0.0994 ± 7	0.3673 ± 17	7.85 ± 4	0.15503 ± 37	84	2402 ± 4
96pc119-8	225	159	0.71	115	0.00005	0.074	0.1961 ± 11	0.1205 ± 11	0.4343 ± 24	9.73 ± 7	0.16243 ± 60	94	2481 ± 6
96pc119-9	336	172	0.51	131	0.00013	0.207	0.1480 ± 11	0.0994 ± 10	0.3444 ± 18	7.42 ± 5	0.15617 ± 61	79	2415 ± 7
96pc119-10	581	308	0.53	252	0.00003	0.047	0.1419 ± 6	0.1035 ± 7	0.3871 ± 18	8.53 ± 5	0.15989 ± 39	86	2454 ± 4
96pc119-11	175	120	0.69	98	0.00005	0.085	0.1926 ± 13	0.1334 ± 13	0.4755 ± 30	11.02 ± 9	0.16804 ± 70	99	2538 ± 7
96pc119-12	775	889	1.15	315	0.00047	0.753	0.3092 ± 12	0.0858 ± 5	0.3184 ± 14	6.20 ± 4	0.14135 ± 52	79	2244 ± 6
96pc119-13	272	123	0.45	107	0.00011	0.180	0.1730 ± 13	0.1292 ± 13	0.3378 ± 19	7.74 ± 6	0.16617 ± 74	74	2519 ± 7
96pc119-14	410	173	0.42	202	0.00006	0.093	0.1173 ± 7	0.1234 ± 11	0.4451 ± 22	10.16 ± 6	0.16549 ± 49	94	2513 ± 5

(*continued*)

Table 1. *Continued*

Spot	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	$^{204}Pb/^{206}Pb$	% f^{206a}	$^{208}Pb^*/^{206}Pb^*$	$^{208}Pb^*/^{232}Th$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$	% conc.	Age $^{207}Pb^*/^{206}Pb^*$
96pc119-15	481	248	0.52	217	0.00006	0.090	0.1403 ± 8	0.1091 ± 9	0.4009 ± 20	9.07 ± 5	0.16407 ± 48	87	2498 ± 5
96pc119-16	1712	787	0.46	331	0.00040	0.637	0.1374 ± 10	0.0529 ± 5	0.1767 ± 7	2.60 ± 2	0.10684 ± 49	60	1746 ± 8
96pc119-17	202	99	0.49	89	0.00013	0.210	0.1567 ± 14	0.1228 ± 14	0.3851 ± 23	8.56 ± 7	0.16116 ± 76	85	2468 ± 8
96pc119-18	159	109	0.68	78	0.00026	0.413	0.2147 ± 19	0.1280 ± 15	0.4081 ± 27	9.26 ± 9	0.16447 ± 95	88	2502 ± 10
96pc119-19	171	174	1.02	99	0.00016	0.260	0.2899 ± 18	0.1311 ± 13	0.4606 ± 29	10.53 ± 9	0.16585 ± 81	97	2516 ± 8
96pc119-20	250	193	0.77	137	0.00006	0.099	0.2094 ± 11	0.1255 ± 11	0.4617 ± 25	10.59 ± 7	0.16635 ± 60	97	2521 ± 6
96pc119-21	275	154	0.56	138	0.00004	0.070	0.1555 ± 9	0.1227 ± 11	0.4410 ± 24	10.16 ± 7	0.16713 ± 57	93	2529 ± 6
96pc119-22	1710	3177	1.86	433	0.00013	0.204	0.4669 ± 11	0.0462 ± 2	0.1837 ± 9	3.17 ± 2	0.12504 ± 37	54	2029 ± 5
96pc119-23	433	511	1.18	230	0.00005	0.087	0.3130 ± 10	0.1107 ± 7	0.4172 ± 21	9.28 ± 6	0.16138 ± 44	91	2470 ± 5
96pc119-24	220	210	0.95	102	0.00014	0.228	0.1714 ± 14	0.0721 ± 8	0.4007 ± 24	8.98 ± 7	0.16256 ± 73	88	2482 ± 8
96pc119-25	457	313	0.68	211	0.00006	1.010	0.1856 ± 8	0.1076 ± 8	0.3968 ± 19	9.01 ± 5	0.16461 ± 46	86	2504 ± 5
96pc119-26	455	212	0.47	160	0.00011	0.181	0.1262 ± 9	0.0859 ± 8	0.3174 ± 16	6.69 ± 4	0.15291 ± 51	75	2379 ± 6
96pc119-27	229	169	0.74	125	0.00023	0.374	0.1934 ± 14	0.1213 ± 12	0.4631 ± 26	10.55 ± 8	0.16519 ± 72	98	2510 ± 7
96pc119-28	167	97	0.58	85	0.00013	0.203	0.1454 ± 13	0.1126 ± 13	0.4468 ± 28	10.13 ± 8	0.16441 ± 74	95	2502 ± 8
96pc119-29	177	98	0.56	91	0.00011	0.173	0.1537 ± 13	0.1240 ± 14	0.4493 ± 28	10.19 ± 8	0.16445 ± 74	96	2502 ± 8
96pc119-30	253	98	0.39	122	0.00006	0.103	0.1088 ± 9	0.1231 ± 13	0.4390 ± 24	9.87 ± 7	0.16307 ± 60	94	2488 ± 6
96pc119-31	483	306	0.63	202	0.00002	0.035	0.1639 ± 7	0.0949 ± 7	0.3667 ± 18	8.03 ± 5	0.15878 ± 43	82	2443 ± 5
96pc119-32	443	297	0.67	212	0.00004	0.069	0.1890 ± 7	0.1161 ± 8	0.4109 ± 19	9.21 ± 5	0.16262 ± 40	89	2483 ± 4
96pc119-33	424	225	0.53	149	0.00030	0.474	0.1835 ± 13	0.1036 ± 9	0.2997 ± 14	6.69 ± 4	0.16182 ± 64	68	2475 ± 7
96pc119-34	745	552	0.74	256	0.00004	0.056	0.1983 ± 7	0.0791 ± 5	0.2957 ± 13	6.03 ± 3	0.14798 ± 36	72	2323 ± 4
96pc119-35	691	380	0.55	245	0.00009	0.144	0.1373 ± 6	0.0794 ± 5	0.3177 ± 14	6.74 ± 4	0.15395 ± 38	74	2390 ± 4
96pc119-36	288	211	0.73	157	0.00007	0.114	0.2048 ± 10	0.1287 ± 10	0.4609 ± 25	10.55 ± 7	0.16597 ± 53	97	2517 ± 5
96pc119-37	351	256	0.73	160	0.00009	0.141	0.1813 ± 9	0.0976 ± 8	0.3925 ± 19	8.81 ± 5	0.16279 ± 52	86	2485 ± 5
96pc119-38	616	291	0.47	239	0.00008	0.130	0.1295 ± 7	0.0959 ± 7	0.3500 ± 16	7.42 ± 4	0.15378 ± 40	81	2388 ± 4
Sample 96-PC-115													
pc115-1	70	24	0.34	37	0.00096	1.537	0.0976 ± 60	0.1332 ± 91	0.4644 ± 123	10.76 ± 37	0.16806 ± 309	97	2538 ± 31
pc115-2	113	42	0.38	55	0.00071	1.139	0.1098 ± 40	0.1249 ± 56	0.4270 ± 107	9.76 ± 29	0.16585 ± 210	91	2516 ± 21
pc115-3	56	27	0.48	32	0.00070	1.123	0.1324 ± 70	0.1363 ± 82	0.4895 ± 131	11.26 ± 40	0.16685 ± 346	102	2526 ± 35
pc115-4	64	38	0.59	35	0.00056	0.895	0.1561 ± 55	0.1238 ± 56	0.4699 ± 125	10.72 ± 36	0.16547 ± 201	99	2512 ± 29
pc115-5	362	376	1.04	80	0.00086	1.379	0.1629 ± 41	0.0292 ± 10	0.1859 ± 45	4.23 ± 12	0.16514 ± 199	44	2509 ± 20
pc115-6	190	195	1.03	95	0.00055	0.873	0.1938 ± 29	0.0786 ± 23	0.4162 ± 101	9.50 ± 25	0.16562 ± 146	89	2514 ± 15
pc115-7	83	34	0.41	47	0.00058	0.921	0.1195 ± 45	0.1447 ± 67	0.4993 ± 128	11.51 ± 35	0.16714 ± 230	103	2529 ± 23
pc115-8	74	25	0.34	37	0.00084	1.338	0.1057 ± 53	0.1366 ± 78	0.4354 ± 123	10.17 ± 33	0.16939 ± 270	91	2552 ± 27
pc115-9	87	31	0.35	47	0.00067	1.069	0.0994 ± 46	0.1341 ± 72	0.4789 ± 124	11.26 ± 35	0.17056 ± 241	98	2563 ± 24
pc115-10	260	190	0.73	143	0.00025	0.395	0.2001 ± 20	0.1266 ± 34	0.4620 ± 112	10.62 ± 27	0.16673 ± 106	97	2525 ± 11
pc115-11	124	89	0.72	71	0.00056	0.902	0.2038 ± 37	0.1338 ± 42	0.4713 ± 118	10.79 ± 31	0.16606 ± 186	99	2518 ± 19
pc115-12	113	96	0.85	52	0.00099	1.585	0.1113 ± 54	0.0525 ± 29	0.3993 ± 101	8.97 ± 28	0.16290 ± 266	87	2486 ± 27
pc115-13	84	41	0.49	47	0.00092	1.472	0.1262 ± 50	0.1228 ± 59	0.4759 ± 122	10.94 ± 34	0.16678 ± 252	99	2526 ± 25
pc115-14	86	31	0.36	44	0.00040	0.640	0.1023 ± 39	0.1311 ± 62	0.4587 ± 117	10.57 ± 32	0.16705 ± 213	96	2528 ± 21
pc115-15	253	361	1.43	74	0.00160	2.560	0.1611 ± 52	0.0268 ± 11	0.2375 ± 58	5.31 ± 16	0.16206 ± 248	55	2477 ± 26

[a] $f^{206}Pb$ is the percentage of common ^{206}Pb in the total measured Pb.

*Radiogenic lead corrected using ^{204}Pb.

% conc. = % concordance defined as [($^{206}Pb/^{238}U$ age)/($^{207}Pb/^{206}Pb$ age)] × 100.

alteration of biotite to chlorite at fold hinges, commonly accompanied by calcite. The rock is partially retrogressed from the amphibolite facies.

The zircons are stubby, subhedral, pale-pink to red grains with well-formed prism faces, but with somewhat rounded terminations, with an average length to width ratio of 1.5:1. The darker grains are commonly more metamict. Inclusions of titanite and apatite are common.

Baizhiyan 'Formation'. Sample 96-PC-115 was obtained from within the Ekou Iron Mine, where it is overlain by amphibolite and BIF. The rock is a fine-grained, dark-grey, mesocratic andesite of fairly massive appearance, with numerous carbonate veins that transgress the fabric. It is composed of equidimensional quartz and untwinned feldspar, with abundant laths of chlorite and muscovite showing strong alignment. Later calcite also forms isolated crystals associated with the felsic minerals. There are some irregular opaque mineral grains. Based on assemblages from other rock-types in the mine, the rock is considered to be retrogressed from the amphibolite facies.

The zircons are colourless to pale pink, elongate crystals with well-developed prism and pyramid faces, although some surface pitting is evident. The length to width ratio varies from 2:1 to 5:1. Some crystals show distinct oscillatory zoning. There are a few inclusions of apatite in certain grains.

Hongmenyan 'Formation'. Samples were obtained between the original 32 and 35 km road markers on the Taihuai–Shahe road across Wutai Mountain. The rocks range from basaltic andesite to rhyodacite in composition and are associated with units of basalt and volcanoclastic sediments. Some of the more felsic units are locally transgressive, and may include subvolcanic intrusions. Petrographically, they all show evidence of strong deformation, with local mylonitic fabrics, and have been metamorphosed to greenschist facies. Geochemical data indicate that the felsic volcanics are calc-alkaline in nature, with basaltic andesites and some andesite samples showing slight LREE enrichment and weak to negligible Eu anomalies, whereas the more dacitic and rhyolitic samples show greater LREE enrichment and more pronounced Eu anomalies (Wilde & Wang 1995; Wang *et al.* in press).

Sample WT 9 is from a 2–2.5-metre-wide unit of fine-grained, grey, leucocratic dacite, with strong layering defined by chlorite. The rock has a pronounced deformation fabric, with aligned chlorite and muscovite grouped into weakly defined layers. The felsic components have straight to curved boundaries and consist of equidimensional quartz and untwinned feldspar. There are also scattered relict microphenocrysts of feldspar and quartz, partially wrapped around by chlorite and white mica. Some epidote veins occur oblique to the foliation.

The zircons are pale pink, euhedral, stubby to elongate crystals with length to width ratios of 1.5:1 to 3:1. Most crystals are clear and devoid of inclusions, but rare grains have rounded inclusions of titanite and needle-like apatite.

Sample WT 12 is from an 8-metre-wide unit of massive, fine-grained, white, leucocratic rhyodacite that is slightly transgressive to the regional foliation. The rock may have been intrusive. It preserves a microporphyritic igneous texture, consisting of abundant, albite-twinned plagioclase and rarer quartz phenocrysts, set in a groundmass of equidimensional to weakly aligned quartz and untwinned feldspar and strongly aligned muscovite. The latter is evenly distributed, although it does form local clusters, especially where it partially wraps around the relict microphenocrysts. There are a few late veins of coarser-grained muscovite and calcite.

The zircons are clear and pale pink, with euhedral prismatic faces and pyramidal terminations. Most are elongate, with length to width ratios of 1.5:1 to 5:1. There is weak oscillatory zoning, and some faces show surface frosting.

Sample WT 13 is from a 4-metre-wide unit of fine-grained, creamy-white, leucocratic rhyolite. Its overall fabric is similar to Sample WT 9, with chlorite concentrated into layers that define the main foliation. Muscovite is also strongly aligned and is associated with equidimensional quartz and weakly aligned untwinned feldspar. A few relict microphenocrysts of plagioclase and quartz occur scattered throughout the rock.

The zircons are well-formed, colourless to pale-pink, stubby grains with length to width ratios of 1.5:1 to 2:1. There are rare rod-like inclusions of apatite.

Sample WT 17 is a rhyodacitic lava also collected from this road section. It is a pale-pink to cream, leucocratic rock, composed of somewhat larger crystals of plagioclase and quartz set in a polygonal matrix of quartz and feldspar with minor chlorite. Muscovite is abundant and strongly aligned.

The zircons are pale pink, with well-formed prismatic faces and pyramidal terminations. Although the age and concordia diagram have previously been published (Wilde *et al.* 1997), the full data-set has not, and we include it in this paper for completeness.

Gaofan 'Subgroup'. Sample 95-PC-55c was collected from a riverbank near Xiazhuan village. It is a pale greenish-grey, leucocratic, felsic schist, interleaved with fine-grained chlorite-rich mafic volcanics, some of which contain garnet, and associated with strongly deformed granitoids which are locally mylonitic. It contains original porphyroblasts of garnet, now totally replaced by chlorite, and is composed of an aggregate of quartz and untwinned feldspar (mostly zoned plagioclase), between schistose layers dominated by chlorite and muscovite. Granular epidote is common within the felsic areas, but is independent of the feldspar. There is evidence of local recrystallization of the initial straight quartz and feldspar grain boundaries to abundant sub-grains. Certain layers are coarser grained and composed of quartz, muscovite, chlorite and calcite. Although now at greenschist facies, the rock was originally at a higher grade, possibly reaching the amphibolite facies, and is interpreted as a tuff.

The zircons are pink, rather stubby grains, mostly with length to width ratios of 1.5:1, but reaching a maximum of 2:1. Crystal faces tend to be slightly irregular, and there is extensive surface pitting. Many grains are slightly metamict and show internal fractures.

Analytical procedures

Following crushing, zircon crystals were extracted from the samples using a combination of heavy liquids and magnetic separation techniques. Individual crystals were hand picked and mounted, along with pieces of the Curtin University Sri Lankan zircon standard (CZ3), on to double-sided adhesive tape and then enclosed in epoxy resin discs. The discs were ground and polished, so as to effectively cut all zircon grains in half, and the samples were then gold coated.

The U–Th–Pb analyses of the zircons were performed using the SHRIMP II ion microprobe at Curtin University, Perth, Western Australia, following standard operating techniques (Nelson 1997; Williams 1998). An average mass resolution of 4800 was recorded during measurement of the Pb/Pb and Pb–U isotopic ratios and Pb–U ratios were normalized to those measured on the standard zircon [CZ3 – (^{206}Pb–^{238}U = 0.0914)], to compensate for elemental discrimination that occurs during sputter ionization (Kinny *et al.* 1993). The conventionally measured age of the standard is 564 Ma (Pidgeon *et al.* 1993) and the error associated with the measurement of Pb–U isotopic ratios for the standard, at one standard deviation, averaged *c.*1.64%. The measured ^{204}Pb values in the unknowns were similar to those recorded for the standard zircon, and so common lead corrections were made, assuming an isotopic composition of Broken Hill lead, since the common lead is considered to be mainly associated with surface contamination in the gold coating (Nelson 1997). The analytical spot size averaged *c.*30 μm during each analytical run, and each spot was rastered over 100 μm for three to five minutes prior to analysis to remove common Pb on the surface or contamination from the gold coating. Data reduction was performed using the Krill 007 program of P. D. Kinny at Curtin University and applying the ^{204}Pb correction. Errors on individual analyses are at the 1σ level whereas errors on pooled analyses are quoted at the 2σ level.

Results

Zhuangwang 'Formation'. The data for samples 96-PC-114 and 96-PC-119 are presented in Table 1 and shown on concordia plots in Figs 4a and 4b. For sample 96-PC-114, 25 analyses on 25 zircons were made, along with 12 analyses of the standard (CZ3) that gave an error of 2.75% over the analytical period. The data can be broadly grouped into two sets, those with low U and Th, and those with slightly higher values (Table 1). The former have U values ranging from 34 to 95 ppm, and Th from 19 to 89 ppm, whereas the latter have U contents of 113 to 186 ppm, and Th contents of 127 to 148 ppm. However, both sets show similar Th–U ratios, which range from 0.30 to 1.23 (average 0.74) (Table 1). With two exceptions, the data are concordant in the range of 94–104% (Table 1). The majority of the analyses, 21 zircons, define a ^{207}Pb/^{206}Pb age of 2529 ± 10 Ma (Fig. 4a). Three analyses are considerably older, with the two most concordant data points giving a ^{207}Pb/^{206}Pb age of 2679 ± 16 Ma (Fig. 4a).

A total of 38 zircons, along with 11 analyses of the standard that gave an error of 0.52%, were analysed from sample 96-PC-119. This sample is quite distinct in zircon chemistry from the above, revealing considerably higher U and Th values and having much higher total Pb contents (Table 1). The U ranges from 47 to 1712 ppm, and the Th from 16 to 3177 ppm, although the range in Th/U ratios is similar, varying from 0.34 to 1.86 (average 0.69) (Table 1). On the concordia diagram (Fig. 4b), the data define a pronounced discordia line trending to zero million years – suggestive of recent lead loss. However, in terms of (^{206}Pb–^{238}U)/(^{207}Pb/^{206}Pb) systematics (see Table 1), the data are fairly concordant (Table 1). If the 16

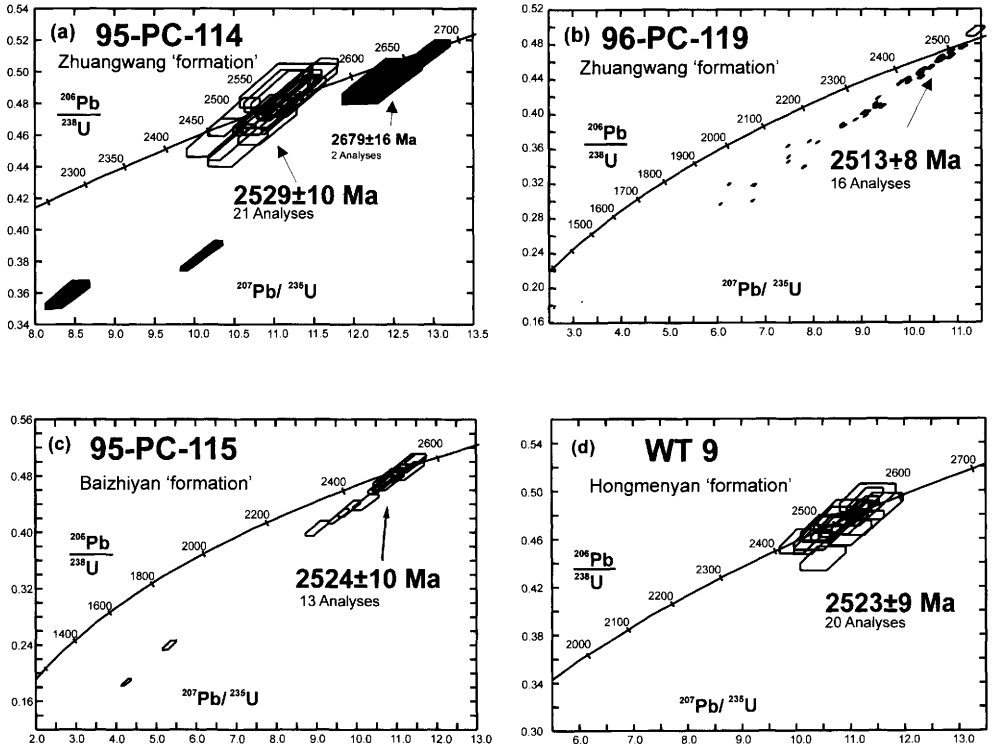

Fig. 4. (**a**) Concordia diagram of sample 96-PC-114 from the Zhuangwang 'Formation'; (**b**) Concordia diagram of sample 96-PC-119 from the Zhuangwang 'Formation'; (**c**) Concordia diagram of sample 96-PC-115 from the Baizhiyan 'Formation'; (**d**) Concordia diagram of sample WT 9 from the Hongmenyan 'Formation'.

most concordant data points are taken, the weighted mean $^{207}Pb/^{206}Pb$ date is 2513 ± 8 Ma (Fig. 4b), and this is taken to be the time of igneous crystallization. This is within the error of the main population of zircons in sample 96-PC-114 and indicates a possible range of crystallization age for the Zhuangwang 'Formation' of *c.*2530–2515 Ma.

Baizhiyan 'Formation'. The data for sample 96-PC-115 are presented in Table 1 and on a concordia diagram in Figure 4c. A total of 15 analyses were made on 15 zircons, along with 12 of the standard which recorded an error of 2.75%. There is some variation in both the U and Th data, with the former ranging from 56–362 ppm and the latter from 24–376 ppm. However, variation in the Th–U ratio is similar to samples from the Zhuangwang 'Formation', ranging from 0.34 to 1.43 (average 0.64). With two exceptions (analyses 115-PC-5 and 115-PC-15 in Table 1) the data are concordant with respect to the $(^{206}Pb/^{238}U)/(^{207}Pb/^{206}Pb)$ system, although they do define a distinct discordia line trending to zero million years in the concordia plot (Fig. 4c). The 13 most concordant analyses from 13 individual zircon crystals give a weighted mean $^{207}Pb/^{206}Pb$ date of 2524 ± 10 Ma. This is interpreted as the crystallization age of the Baizhiyan 'Formation' and is within the range exhibited by the two samples from the Zhuangwang 'Formation'.

Hongmenyan 'Formation'. The data from the four samples analysed in this study are presented in Table 2 and on concordia diagrams in Figure 4d and Figure 5a, b and c. The most striking features of the data are their close similarity in age, their concordance and the lack of any inheritance.

For sample WT 9, a total of 20 analyses were made on 20 zircons, along with seven analyses of the standard, which recorded an error of 1.00% during the analytical session. The zircons are remarkably uniform in their chemistry, with U ranging from 32 to 73 ppm, and Th from 16 to 52 ppm; the Th–U ratio shows a small range from 0.47 to 0.71 (average 0.58), (Table 2). The zircons are concordant (92–103%), and define a single population with a weighted mean $^{207}Pb/^{206}Pb$ age of 2523 ± 9 Ma (Fig. 4d).

Table 2. *SHRIMP U–Pb–Th zircon data for Wutai Volcanic samples WT 9, WT 12 and WT 13*

Spot	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	$^{204}Pb/^{206}Pb$	$\%f^{206a}$	$^{208}Pb^*/^{206}Pb^*$	$^{208}Pb^*/^{232}Th$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$	% conc.	Age $^{207}Pb^*/^{206}Pb^*$
Sample WT 9													
WT9-1	37	22	0.60	30	0.00158	2.623	0.1723 ± 105	0.1371 ± 91	0.4778 ± 107	10.76 ± 41	0.16334 ± 469	101	2491 ± 48
WT9-2	43	20	0.47	25	0.00155	2.491	0.1323 ± 90	0.1341 ± 98	0.4748 ± 104	11.27 ± 39	0.17210 ± 413	97	2578 ± 40
WT9-3	73	52	0.71	43	0.00054	0.859	0.2007 ± 56	0.1369 ± 49	0.4824 ± 100	11.26 ± 30	0.16932 ± 253	99	2551 ± 25
WT9-4	33	19	0.57	19	0.00242	3.307	0.1191 ± 134	0.0948 ± 110	0.4515 ± 105	9.48 ± 45	0.15224 ± 597	101	2371 ± 67
WT9-5	46	32	0.70	27	0.00079	1.276	0.1954 ± 71	0.1332 ± 59	0.4760 ± 103	11.02 ± 34	0.16788 ± 324	99	2537 ± 32
WT9-6	34	18	0.54	20	0.00162	2.596	0.1537 ± 114	0.1389 ± 110	0.4888 ± 113	11.53 ± 46	0.17115 ± 514	100	2569 ± 50
WT9-7	33	18	0.57	19	0.00167	2.666	0.1441 ± 123	0.1228 ± 111	0.4830 ± 113	10.89 ± 47	0.16355 ± 554	102	2493 ± 57
WT9-8	69	37	0.54	39	0.00090	1.444	0.1424 ± 60	0.1246 ± 61	0.4732 ± 99	10.75 ± 31	0.16476 ± 278	100	2505 ± 28
WT9-9	41	27	0.65	24	0.00118	1.885	0.1716 ± 88	0.1240 ± 72	0.4693 ± 104	10.67 ± 37	0.16495 ± 399	99	2507 ± 41
WT9-10	39	17	0.43	21	0.00156	2.499	0.1017 ± 99	0.1081 ± 109	0.4597 ± 103	10.1 ± 39	0.15941 ± 451	100	2449 ± 48
WT9-11	35	16	0.47	19	0.00190	3.034	0.1164 ± 123	0.1150 ± 126	0.4629 ± 106	10.43 ± 45	0.16347 ± 556	98	2492 ± 57
WT9-12	35	22	0.63	20	0.00180	2.879	0.1773 ± 116	0.1252 ± 89	0.4450 ± 102	10.52 ± 42	0.17139 ± 522	92	2571 ± 51
WT9-13	39	24	0.63	22	0.00095	1.526	0.1813 ± 93	0.1346 ± 78	0.4663 ± 104	11.02 ± 39	0.17138 ± 419	96	2571 ± 41
WT9-14	52	28	0.54	29	0.00134	2.145	0.1313 ± 77	0.1122 ± 72	0.4590 ± 99	10.32 ± 33	0.16299 ± 352	98	2487 ± 36
WT9-15	47	33	0.70	28	0.00057	0.914	0.1954 ± 58	0.1354 ± 53	0.4829 ± 104	11.13 ± 32	0.16710 ± 266	100	2529 ± 27
WT9-16	56	33	0.59	33	0.00097	1.549	0.1543 ± 65	0.1301 ± 64	0.4937 ± 105	11.29 ± 34	0.16588 ± 301	103	2516 ± 31
WT9-17	36	20	0.56	20	0.00126	2.016	0.1362 ± 106	0.1153 ± 95	0.4697 ± 107	10.55 ± 42	0.16293 ± 480	100	2486 ± 50
WT9-18	59	41	0.68	35	0.00052	0.832	0.1945 ± 56	0.1385 ± 52	0.4870 ± 103	11.25 ± 31	0.16751 ± 258	101	2533 ± 26
WT9-19	35	19	0.56	20	0.00172	2.755	0.1385 ± 118	0.1173 ± 105	0.4711 ± 109	10.56 ± 45	0.16263 ± 530	100	2483 ± 55
WT9-20	32	18	0.54	20	0.00205	3.285	0.1414 ± 134	0.1290 ± 128	0.4961 ± 117	11.36 ± 52	0.16604 ± 602	103	2518 ± 61
Sample WT 12													
WT12-1	119	76	0.64	66	0.00047	0.746	0.1721 ± 30	0.1268 ± 38	0.4731 ± 108	10.89 ± 28	0.16697 ± 145	99	2528 ± 15
WT12-2	40	27	0.67	25	0.00049	0.792	0.2081 ± 68	0.1570 ± 67	0.5026 ± 123	12.10 ± 39	0.17459 ± 311	101	2602 ± 30
WT12-3	57	24	0.42	32	0.00132	2.119	0.1088 ± 75	0.1235 ± 91	0.4816 ± 115	10.92 ± 37	0.16451 ± 344	101	2503 ± 35
WT12-4	89	49	0.55	52	0.00111	1.777	0.1329 ± 53	0.1187 ± 56	0.4894 ± 114	11.20 ± 33	0.16591 ± 246	102	2517 ± 25
WT12-5	54	40	0.73	33	0.00132	2.106	0.1915 ± 69	0.1263 ± 57	0.4822 ± 116	10.94 ± 35	0.16462 ± 311	101	2504 ± 32
WT12-6	48	23	0.47	28	0.00175	2.802	0.1122 ± 88	0.1145 ± 95	0.4833 ± 118	10.78 ± 40	0.16184 ± 399	103	2475 ± 42
WT12-7	38	23	0.60	24	0.00273	4.369	0.1524 ± 120	0.1209 ± 101	0.4794 ± 120	10.70 ± 47	0.16195 ± 534	102	2476 ± 56
WT12-8	39	22	0.57	19	0.00193	3.095	0.1553 ± 104	0.1314 ± 96	0.4815 ± 119	11.06 ± 44	0.16656 ± 469	100	2523 ± 47
WT12-9	32	17	0.52	19	0.00286	4.569	0.1185 ± 134	0.1057 ± 124	0.4669 ± 119	10.17 ± 49	0.15804 ± 600	101	2435 ± 64
WT12-10	59	43	0.74	36	0.00150	2.402	0.1788 ± 71	0.1201 ± 57	0.4955 ± 118	11.08 ± 36	0.16216 ± 320	105	2478 ± 33
WT12-11	94	63	0.67	55	0.00094	1.501	0.1754 ± 49	0.1267 ± 47	0.4830 ± 111	11.30 ± 32	0.16961 ± 222	99	2554 ± 22
WT12-12	85	42	0.49	49	0.00140	2.242	0.1166 ± 57	0.1136 ± 63	0.4817 ± 112	10.76 ± 32	0.16200 ± 263	102	2477 ± 27
WT12-13	33	18	0.55	20	0.00206	3.301	0.1481 ± 116	0.1316 ± 110	0.4875 ± 124	11.05 ± 47	0.16448 ± 519	102	2502 ± 53
WT12-14	93	73	0.79	57	0.00059	0.947	0.2165 ± 42	0.1374 ± 43	0.4986 ± 115	11.56 ± 31	0.16817 ± 191	103	2539 ± 19
WT12-15	32	18	0.56	19	0.00163	2.606	0.1513 ± 118	0.1326 ± 111	0.4949 ± 128	11.41 ± 50	0.16727 ± 532	102	2531 ± 53
WT12-16	64	45	0.71	40	0.00077	1.226	0.1948 ± 59	0.1417 ± 57	0.5129 ± 124	11.76 ± 36	0.16635 ± 268	106	2521 ± 27
WT12-17	30	18	0.60	19	0.00129	2.063	0.1655 ± 99	0.1372 ± 93	0.4991 ± 132	11.45 ± 46	0.16636 ± 451	104	2521 ± 46
WT12-18	52	40	0.77	34	0.00099	1.579	0.2023 ± 70	0.1374 ± 62	0.5260 ± 131	11.88 ± 40	0.16389 ± 318	109	2496 ± 33
WT12-19	73	48	0.65	41	0.00070	1.116	0.1805 ± 56	0.1306 ± 53	0.4711 ± 111	10.74 ± 32	0.16538 ± 258	99	2511 ± 26

WT12-20	195	205	1.05	98	0.00045	0.720	0.2729 ± 30	0.1029 ± 26	0.3966 ± 89	9.02 ± 22	0.16497 ± 130	86	2507 ± 13
WT12-21	70	51	0.73	40	0.00100	1.602	0.1933 ± 60	0.1226 ± 50	0.4641 ± 110	10.79 ± 33	0.16863 ± 272	97	2544 ± 27
WT12-22	66	37	0.57	38	0.00114	1.819	0.1570 ± 58	0.1312 ± 59	0.4742 ± 112	10.96 ± 33	0.16757 ± 266	99	2533 ± 27
WT12-23	80	55	0.69	47	0.00094	1.507	0.1795 ± 49	0.1252 ± 46	0.4827 ± 112	10.80 ± 31	0.16228 ± 221	102	2480 ± 23
WT12-24	59	30	0.51	34	0.00096	1.539	0.1308 ± 61	0.1242 ± 67	0.4852 ± 116	11.18 ± 35	0.16717 ± 282	101	2530 ± 28
WT12-25a	23	9	0.40	13	0.00178	2.843	0.1039 ± 135	0.1236 ± 166	0.4770 ± 128	10.89 ± 53	0.16560 ± 615	100	2514 ± 62
WT12-25b	24	9	0.39	14	0.00181	2.904	0.0981 ± 147	0.1208 ± 186	0.4813 ± 129	10.73 ± 56	0.16173 ± 666	102	2474 ± 70
WT12-25c	32	10	0.30	18	0.00247	3.953	0.0380 ± 141	0.0592 ± 220	0.4741 ± 124	10.01 ± 52	0.15317 ± 640	105	2382 ± 71
WT12-26	33	20	0.61	21	0.00166	2.661	0.1552 ± 115	0.1281 ± 103	0.5033 ± 129	11.39 ± 49	0.16417 ± 518	105	2499 ± 53
Sample WT 13													
WT13-1	86	39	0.46	50	0.00077	1.221	0.1296 ± 41	0.1418 ± 52	0.4989 ± 79	11.86 ± 24	0.17247 ± 195	101	2582 ± 19
WT13-2	44	28	0.63	25	0.00024	0.388	0.1696 ± 40	0.1343 ± 42	0.4953 ± 83	11.37 ± 25	0.16648 ± 194	103	2523 ± 20
WT13-3	35	18	0.52	26	0.00022	0.357	0.1542 ± 70	0.1465 ± 75	0.4917 ± 87	11.52 ± 32	0.16995 ± 328	101	2557 ± 32
WT13-4	39	23	0.59	22	0.00035	0.991	0.1602 ± 44	0.1406 ± 49	0.5163 ± 89	11.98 ± 27	0.16824 ± 218	106	2540 ± 22
WT13-5	80	54	0.68	46	0.00033	0.523	0.1839 ± 36	0.1327 ± 36	0.4890 ± 79	11.20 ± 22	0.16617 ± 169	102	2519 ± 17
WT13-6	65	34	0.52	29	0.00021	0.340	0.1496 ± 35	0.1467 ± 45	0.5148 ± 84	11.86 ± 24	0.16706 ± 176	106	2528 ± 18
WT13-7	34	18	0.54	19	0.00067	1.075	0.1422 ± 65	0.1242 ± 65	0.4717 ± 87	10.59 ± 30	0.16285 ± 311	100	2485 ± 32
WT13-8	35	20	0.58	22	0.00082	1.102	0.1472 ± 74	0.1347 ± 74	0.5279 ± 96	11.99 ± 35	0.16477 ± 341	109	2505 ± 35
WT13-9	42	28	0.67	24	0.00053	0.852	0.1831 ± 65	0.1300 ± 54	0.4733 ± 82	10.83 ± 28	0.16596 ± 296	99	2517 ± 30
WT13-10	44	29	0.66	20	0.00015	0.234	0.1910 ± 64	0.1414 ± 56	0.4858 ± 83	11.64 ± 30	0.17373 ± 292	98	2594 ± 28
WT13-11/3	38	18	0.48	20	0.00031	0.507	0.1230 ± 59	0.1224 ± 64	0.4791 ± 81	10.88 ± 28	0.16473 ± 283	101	2505 ± 29
WT13-12	27	15	0.56	15	0.00076	1.223	0.1395 ± 77	0.1164 ± 70	0.4702 ± 86	10.71 ± 32	0.16524 ± 361	99	2510 ± 37
WT13-13	114	78	0.68	63	0.00004	0.058	0.1880 ± 17	0.1320 ± 25	0.4788 ± 72	11.01 ± 18	0.16670 ± 89	100	2525 ± 9
WT13-14	44	31	0.71	26	0.00024	0.380	0.1936 ± 44	0.1344 ± 40	0.4896 ± 80	11.17 ± 24	0.16549 ± 205	102	2513 ± 21
WT13-15	40	20	0.49	22	0.00030	0.479	0.1302 ± 50	0.1314 ± 57	0.4978 ± 82	11.26 ± 26	0.16410 ± 236	104	2498 ± 24
WT13-16	43	26	0.59	25	0.00021	0.341	0.1617 ± 37	0.1345 ± 41	0.4943 ± 81	11.38 ± 24	0.16695 ± 185	102	2527 ± 19
WT13-17a	39	19	0.50	21	0.00027	0.430	0.1354 ± 50	0.1303 ± 55	0.4786 ± 79	10.99 ± 26	0.16661 ± 240	100	2524 ± 24
WT13-17b	40	22	0.55	22	0.00021	0.332	0.1486 ± 38	0.1317 ± 43	0.4857 ± 81	11.23 ± 24	0.16770 ± 194	101	2535 ± 19
WT13-18	60	32	0.53	33	0.00012	0.191	0.1477 ± 28	0.1345 ± 36	0.4867 ± 77	11.25 ± 21	0.16766 ± 145	101	2534 ± 15
WT13-19	34	18	0.53	19	0.00010	0.168	0.1478 ± 44	0.1398 ± 51	0.4980 ± 84	11.73 ± 26	0.17080 ± 221	102	2565 ± 22
WT13-20	34	19	0.56	26	0.00041	0.650	0.1495 ± 54	0.1301 ± 55	0.4914 ± 83	11.31 ± 28	0.16687 ± 258	102	2526 ± 26
WT13-21	32	20	0.62	18	0.00004	0.318	0.1773 ± 31	0.1407 ± 39	0.4893 ± 84	11.47 ± 24	0.17002 ± 165	100	2558 ± 16
WT13-22	41	20	0.48	22	0.00018	0.293	0.1311 ± 40	0.1310 ± 48	0.4826 ± 79	11.18 ± 24	0.16802 ± 199	100	2538 ± 20
WT13-23	29	16	0.56	16	0.00033	0.522	0.1580 ± 50	0.1356 ± 52	0.4785 ± 82	11.05 ± 26	0.16744 ± 244	100	2532 ± 24
WT13-24	48	27	0.56	27	0.00015	0.233	0.1573 ± 35	0.1365 ± 40	0.4839 ± 78	11.30 ± 23	0.16930 ± 174	100	2551 ± 17

[a] f^{206}Pb is the percentage of common ^{206}Pb in the total measured Pb.
* Radiogenic lead corrected using ^{204}Pb.
% conc. = % concordance defined as [(^{206}Pb–^{238}U age)/(^{207}Pb/^{206}Pb age)] × 100.
a, b and c represent multiple analyses within a single zircon crystal.

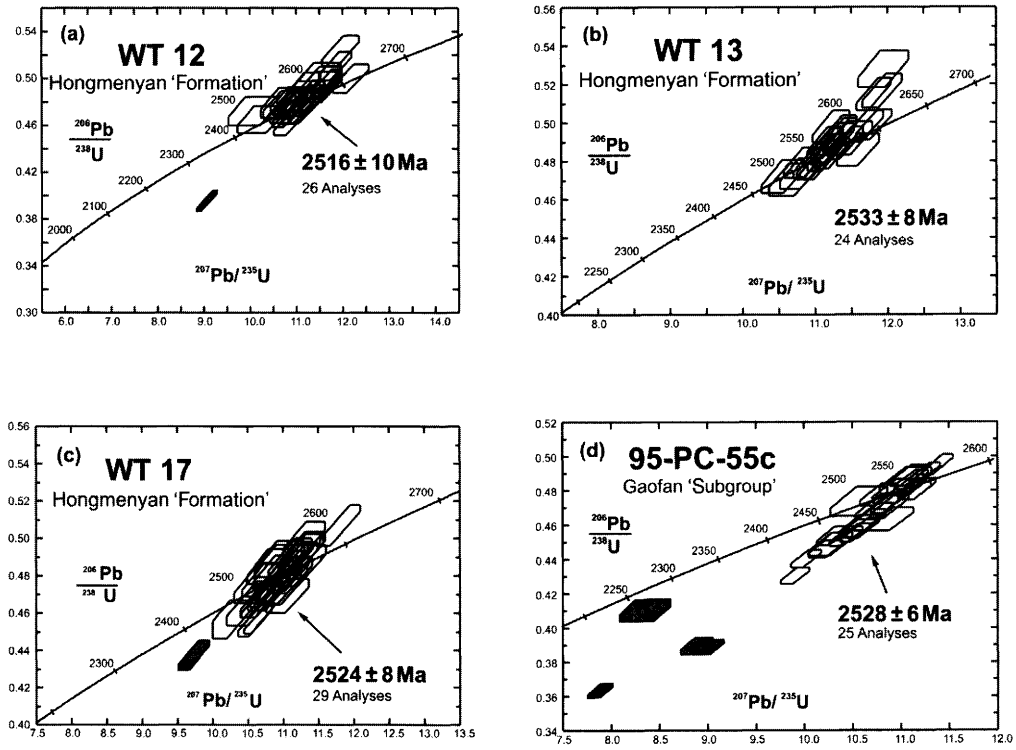

Fig. 5. (**a**) Concordia diagram of sample WT 12 from the Hongmenyan 'Formation'; (**b**) Concordia diagram of sample WT 13 from the Hongmenyan 'Formation'; (**c**) Concordia diagram of sample WT 17 from the Hongmenyan 'Formation'; (**d**) Concordia diagram of sample 95-PC-55c from the Gaofan 'Subgroup'.

A total of 27 analyses were made on 26 zircons from sample WT 12, along with seven analyses of the standard, which recorded an error of 1.61% during the analytical session. With two exceptions (WT 12-1 and WT 12-20 in Table 2), the zircons show little variation in their U and Th contents – these ranging from 23–94 ppm and 9–73 ppm, respectively. The Th–U ratio, with the exception of WT 12-20 which is higher at 1.05, shows little variation, ranging from 0.30 to 0.79 (average 0.61). The data are reasonably concordant (86–109% in Table 2), and the 26 most concordant analyses define a single population with a weighted mean $^{207}Pb/^{206}Pb$ age of 2516 ± 10 Ma (Fig. 5a).

For sample WT 13, a total of 24 analyses on 23 zircons were determined, along with 10 analyses on the standard zircon, which gave an error of 1.45%. With one exception (WT 13-13 in Table 2), the data reveal little variation in U and Th contents, ranging from 27–86 ppm and 15–54 ppm, respectively, with Th–U ratios varying from 0.46–0.71 (average 0.57). The data are reasonably concordant (98–109%) and define a weighted mean $^{207}Pb/^{206}Pb$ age of 2533 ± 8 Ma (Fig. 5b).

For completeness, the data-set for sample WT 17 is also included in this paper (Table 3 and on a concordia plot in Fig. 5d). Thirty analyses were made, along with 10 measurements of the standard, which gave an error of 2.06% during the analytical session. A total of 29 zircon analyses (the exception being WT 17-11) reveal a small range in U and Th contents, varying from 24 to 74 ppm and 9 to 58 ppm, respectively; the Th–U ratio of the total population varies from 0.33 to 0.75 (average 0.53) (Table 3). The data are tightly concordant (95–104%), and define a weighted mean $^{207}Pb/^{206}Pb$ age of 2524 ± 8 Ma.

In summary, all four samples from the Hongmenyan 'Formation' have $^{207}Pb/^{206}Pb$ dates within the range *c.*2533–2516 Ma, that is, indistinguishable from the data from the Zhuangwang 'Formation'.

Gaofan 'Subgroup'. The data-for sample 95-PC-55c are presented in Table 3 and on a concordia plot in Figure 5d. A total of 29 zircons were analysed, along with seven analyses of the standard, which gave an error of 1.00% during the analytical session. The U and Th contents of the zircons range

Table 3. *SHRIMP U–Pb–Th zircon data for Wutai Volcanic samples WT 17 and 95-PC-55c*

Spot	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	$^{204}Pb/^{206}Pb$	$\%\ f^{206a}$	$^{207}Pb^*/^{206}Pb^*$	$^{208}Pb^*/^{206}Pb^*$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{208}Pb^*/^{232}Th$	% conc.	Age $^{207}Pb^*/^{206}Pb^*$
Sample WT 17													
WT-17-1	34	16	0.48	19	0.00009	0.150	0.16887 ± 307	0.1363 ± 64	0.4853 ± 110	11.30 ± 35	0.1372 ± 75	100	2546 ± 30
WT-17-2	37	21	0.58	20	0.00091	1.414	0.16457 ± 320	0.1446 ± 69	0.4564 ± 102	10.36 ± 32	0.1135 ± 62	97	2503 ± 33
WT-17-3	37	22	0.60	21	0.00085	1.156	0.16294 ± 371	0.1542 ± 82	0.4760 ± 107	10.69 ± 36	0.1222 ± 72	101	2486 ± 38
WT-17-4	71	52	0.74	43	0.00033	0.514	0.16961 ± 160	0.2031 ± 34	0.5069 ± 107	11.85 ± 29	0.1397 ± 40	104	2554 ± 16
WT-17-5	36	19	0.54	20	0.00077	1.227	0.16854 ± 322	0.1496 ± 70	0.4752 ± 105	11.04 ± 34	0.1324 ± 71	99	2543 ± 32
WT-17-6	39	19	0.47	23	0.00104	2.010	0.16645 ± 291	0.1360 ± 62	0.4927 ± 108	11.31 ± 34	0.1420 ± 74	102	2522 ± 29
WT-17-7	42	19	0.45	23	0.00025	0.397	0.16712 ± 233	0.1274 ± 48	0.4873 ± 105	11.23 ± 31	0.1385 ± 63	101	2529 ± 23
WT-17-8	38	18	0.48	21	0.00093	1.503	0.16796 ± 312	0.1313 ± 67	0.4739 ± 91	10.97 ± 31	0.1297 ± 73	99	2537 ± 31
WT-17-9	24	11	0.45	13	0.00058	1.358	0.16808 ± 303	0.1368 ± 62	0.4805 ± 97	11.13 ± 32	0.1455 ± 76	100	2539 ± 30
WT-17-10	33	16	0.50	18	0.00068	1.094	0.16214 ± 320	0.1198 ± 69	0.4848 ± 93	10.84 ± 32	0.1171 ± 72	103	2478 ± 33
WT-17-11	105	79	0.75	59	0.00031	0.490	0.16580 ± 124	0.2017 ± 26	0.4659 ± 83	10.65 ± 21	0.1253 ± 29	98	2516 ± 13
WT-17-12	61	26	0.43	33	0.00026	0.423	0.16832 ± 176	0.1187 ± 35	0.4807 ± 88	11.16 ± 25	0.1331 ± 48	100	2541 ± 17
WT-17-13	28	14	0.52	16	0.00167	2.671	0.16414 ± 418	0.1320 ± 92	0.4866 ± 97	11.01 ± 38	0.1236 ± 91	102	2499 ± 43
WT-17-14	55	23	0.41	30	0.00014	0.222	0.16657 ± 170	0.1163 ± 33	0.4891 ± 90	11.23 ± 25	0.1378 ± 49	102	2523 ± 17
WT-17-15	26	9	0.33	15	0.00089	1.426	0.16310 ± 372	0.0828 ± 79	0.4889 ± 97	10.99 ± 35	0.1241 ± 123	103	2488 ± 38
WT-17-16	34	22	0.63	21	0.00079	1.269	0.16473 ± 269	0.1688 ± 58	0.4995 ± 96	11.34 ± 30	0.1335 ± 55	104	2505 ± 27
WT-17-17	41	22	0.55	23	0.00044	0.707	0.16605 ± 218	0.1437 ± 45	0.4843 ± 91	11.09 ± 27	0.1275 ± 49	101	2518 ± 22
WT-17-18	68	40	0.60	36	0.00011	0.305	0.16961 ± 115	0.1661 ± 21	0.4573 ± 83	10.69 ± 21	0.1270 ± 30	95	2554 ± 11
WT-17-19	49	22	0.46	27	0.00123	3.622	0.16355 ± 205	0.1153 ± 42	0.4818 ± 89	10.87 ± 26	0.1206 ± 51	102	2493 ± 21
WT-17-20	51	22	0.43	27	0.00073	1.134	0.16277 ± 231	0.1090 ± 49	0.4776 ± 88	10.72 ± 26	0.1222 ± 61	101	2485 ± 24
WT-17-21	74	58	0.78	42	0.00024	0.381	0.16607 ± 138	0.2182 ± 30	0.4715 ± 85	10.80 ± 22	0.1314 ± 31	99	2518 ± 14
WT-17-22	54	23	0.43	27	0.00028	0.450	0.16182 ± 175	0.1263 ± 35	0.4374 ± 81	9.76 ± 22	0.1279 ± 45	95	2475 ± 18
WT-17-23	38	24	0.64	21	0.00045	0.728	0.16623 ± 245	0.1734 ± 52	0.4669 ± 89	10.70 ± 27	0.1260 ± 47	98	2520 ± 25
WY-17-24	59	25	0.41	30	0.00025	0.396	0.16919 ± 180	0.1130 ± 36	0.4560 ± 84	10.64 ± 24	0.1245 ± 47	95	2550 ± 18
WT-17-25	27	15	0.55	15	0.00030	0.478	0.16692 ± 263	0.1507 ± 54	0.4707 ± 95	10.83 ± 29	0.1290 ± 56	98	2527 ± 26
WT-17-26	34	17	0.51	19	0.00051	0.815	0.17160 ± 295	0.1443 ± 63	0.4690 ± 92	11.10 ± 31	0.1324 ± 66	96	2573 ± 29
WT-17-27	39	21	0.55	22	0.00057	0.921	0.16517 ± 241	0.1504 ± 51	0.4893 ± 107	11.14 ± 31	0.1329 ± 56	102	2509 ± 25
WT-17-28	41	28	0.68	24	0.00056	0.896	0.16667 ± 266	0.1816 ± 58	0.4914 ± 107	11.29 ± 32	0.1319 ± 53	102	2524 ± 27
WT-17-29	30	19	0.63	17	0.00073	1.174	0.16525 ± 330	0.1729 ± 72	0.4637 ± 105	10.57 ± 34	0.1274 ± 63	98	2510 ± 34
WT-17-30	35	15	0.43	19	0.00062	0.986	0.16656 ± 284	0.1137 ± 59	0.4768 ± 106	10.95 ± 32	0.1264 ± 74	100	2523 ± 29

(*continued*)

Table 3. *Continued*

Spot	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	$^{204}Pb/^{206}Pb$	% f^{206a}	$^{207}Pb^*/^{206}Pb^*$	$^{208}Pb^*/^{206}Pb^*$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{208}Pb^*/^{232}Th$	% conc.	Age $^{207}Pb^*/^{206}Pb^*$
Sample 95-PC-55c													
95pc55c-1	113	83	0.74	66	0.00002	0.032	0.1999 ± 19	0.1342 ± 22	0.4945 ± 59	11.40 ± 16	0.16724 ± 111	102	2530 ± 11
95pc55c-2	66	26	0.40	33	0.00000	0.000	0.1155 ± 14	0.1331 ± 27	0.4575 ± 61	10.63 ± 17	0.16852 ± 133	95	2543 ± 13
95pc55c-3	68	33	0.48	36	0.00015	0.244	0.1297 ± 29	0.1285 ± 35	0.4772 ± 65	10.79 ± 19	0.16400 ± 169	101	2497 ± 17
95pc55c-4	81	38	0.46	44	0.00019	0.299	0.1235 ± 29	0.1299 ± 37	0.4883 ± 65	11.10 ± 20	0.16487 ± 166	102	2506 ± 17
95pc55c-5	121	55	0.45	60	0.00012	0.186	0.1211 ± 24	0.1181 ± 28	0.4399 ± 53	10.03 ± 16	0.16542 ± 141	94	2512 ± 14
95pc55c-6	63	26	0.42	32	0.00001	0.020	0.1191 ± 39	0.1314 ± 49	0.4628 ± 68	10.92 ± 23	0.17120 ± 218	95	2569 ± 21
95pc55c-7	72	37	0.52	37	0.00011	0.170	0.1391 ± 38	0.1237 ± 40	0.4585 ± 65	10.58 ± 21	0.16742 ± 205	96	2532 ± 21
95pc55c-8	108	53	0.49	55	0.00008	0.132	0.1355 ± 26	0.1246 ± 30	0.4528 ± 58	10.45 ± 17	0.16739 ± 152	95	2532 ± 15
95pc55c-9	45	18	0.40	24	0.00031	0.503	0.1017 ± 51	0.1228 ± 66	0.4852 ± 79	11.07 ± 27	0.16551 ± 267	101	2513 ± 27
95pc55c-10	160	85	0.53	89	0.00008	0.133	0.1431 ± 18	0.1311 ± 24	0.4900 ± 57	11.26 ± 16	0.16672 ± 109	102	2525 ± 11
95pc55c-11	171	179	1.05	95	0.00150	2.396	0.1824 ± 41	0.0776 ± 20	0.4456 ± 51	10.24 ± 18	0.16661 ± 194	94	2524 ± 20
95pc55c-12	207	188	0.91	106	0.00087	1.395	0.1645 ± 30	0.0777 ± 17	0.4297 ± 47	9.91 ± 15	0.16734 ± 151	91	2531 ± 15
95pc55c-13	63	25	0.39	31	0.00026	0.422	0.0985 ± 43	0.1131 ± 53	0.4481 ± 67	10.29 ± 22	0.16660 ± 231	95	2524 ± 23
95pc55c-14	241	498	2.06	126	0.00206	3.290	0.2509 ± 45	0.0472 ± 10	0.3884 ± 43	9.02 ± 16	0.16841 ± 205	83	2542 ± 20
95pc55c-15	190	244	1.28	86	0.00068	1.088	0.2447 ± 34	0.0694 ± 13	0.3629 ± 41	7.89 ± 13	0.15761 ± 163	82	2430 ± 18
95pc55c-16	51	17	0.34	24	0.00127	2.027	0.1002 ± 82	0.1217 ± 10	0.4097 ± 62	8.36 ± 26	0.14792 ± 386	95	2322 ± 45
95pc55c-17	40	18	0.45	21	0.00044	0.698	0.1125 ± 63	0.1194 ± 72	0.4730 ± 83	10.59 ± 30	0.16229 ± 322	101	2480 ± 33
95pc55c-18	128	156	1.22	59	0.00139	2.220	0.1230 ± 46	0.0393 ± 16	0.3889 ± 47	8.89 ± 17	0.16585 ± 222	84	2516 ± 22
95pc55c-19	148	106	0.72	77	0.00032	0.505	0.1394 ± 25	0.0881 ± 20	0.4546 ± 53	10.54 ± 16	0.16817 ± 135	95	2539 ± 13
95pc55c-20	146	96	0.66	80	0.00015	0.235	0.1769 ± 22	0.1264 ± 23	0.4717 ± 55	10.87 ± 16	0.16715 ± 125	98	2529 ± 13
95pc55c-21	185	92	0.50	100	0.00004	0.060	0.1358 ± 16	0.1310 ± 22	0.4813 ± 54	11.14 ± 15	0.16786 ± 99	100	2536 ± 10
95pc55c-22	138	97	0.70	71	0.00038	0.606	0.1365 ± 26	0.0880 ± 21	0.4530 ± 54	10.30 ± 16	0.16498 ± 142	96	2507 ± 14
95pc55c-23	98	62	0.63	55	0.00010	0.159	0.1696 ± 29	0.1297 ± 29	0.4804 ± 62	11.20 ± 19	0.16904 ± 158	99	2548 ± 16
95pc55c-24	62	24	0.38	32	0.00017	0.270	0.1025 ± 38	0.1253 ± 51	0.4695 ± 69	10.77 ± 22	0.16640 ± 211	98	2522 ± 21
95pc55c-25	86	45	0.53	45	0.00004	0.068	0.1523 ± 30	0.1338 ± 34	0.4620 ± 62	10.67 ± 19	0.16756 ± 171	97	2533 ± 17
95pc55c-26	126	57	0.45	68	0.00010	0.156	0.1231 ± 21	0.1314 ± 29	0.4826 ± 58	11.11 ± 17	0.16699 ± 127	100	2528 ± 13
95pc55c-27	55	25	0.45	28	0.00000	0.000	0.1177 ± 16	0.1228 ± 28	0.4702 ± 71	10.90 ± 20	0.16813 ± 147	98	2539 ± 15
95pc55c-28	121	63	0.52	66	0.00005	0.078	0.1437 ± 23	0.1337 ± 28	0.4858 ± 58	11.13 ± 17	0.16619 ± 132	101	2520 ± 13
95pc55c-30	55	23	0.41	30	0.00037	0.596	0.1149 ± 50	0.1332 ± 62	0.4789 ± 71	10.98 ± 25	0.16623 ± 256	100	2520 ± 26

[a] $f^{206}Pb$ is the percentage of common ^{206}Pb in the total measured Pb.

* Radiogenic lead corrected using ^{204}Pb.

% conc. = % concordance defined as [($^{206}Pb/^{238}U$ age)/($^{207}Pb/^{206}Pb$ age)] × 100.

from 40 to 241 ppm and 17 to 498 ppm, respectively, with a range in the Th–U ratio from 0.38 to 2.06 (average 0.64). All bar four of the analyses are reasonably concordant (91–102%, Table 3) and these remaining 25 analyses define a weighted mean $^{207}Pb/^{206}Pb$ age of 2528 ± 6 Ma.

Interpretation

Zircons from all specimens show strong oscillatory zoning in cathodoluminesence imagery, indicative of magmatic growth. Furthermore, the metamorphic grade of greenschist to lower amphibolite facies is too low to allow metamorphic zircon growth and all grains, including the inherited population in sample 96-PC-114, are considered to reflect igneous ages.

The dating results from the seven new specimens analysed, together with sample WT 17 from Wilde *et al.* (1997), are summarized in Table 4. It is evident that:

(1) all the dates are essentially similar within error;
(2) there is no consistent trend of upward younging from what has been interpreted as the base of the Wutai succession (Tian 1991); and,
(3) there is more variability within what were considered to be single 'formations' than there is between units supposedly near the top and bottom of the sequence.

Although the weighted mean ages of the eight individual samples do not overlap within two sigma error (Table 4), collectively, the data sets do overlap without a time break, extending from the youngest date of 2513 ± 8 Ma (96-PC-119) to the oldest date of 2533 ± 8 Ma (WT 13). If the 149 most concordant zircon analyses are treated as a single population from one magmatic episode, the calculated weighted mean $^{207}Pb/^{206}Pb$ age is 2523 ± 3 Ma; we consider this to be the best estimate of the general age of felsic volcanism in the Wutai Complex. More than one age is possibly represented in the suite, but the fairly large error recorded for individual populations, coupled with the slightly discordant nature of several analyses, precludes a thorough evaluation of this aspect. However, the overall similarity in both age and zircon chemistry of the volcanic rocks, together with their whole-rock geochemistry (Wang *et al.* in press), suggests that they represent essentially the products of one magmatic event.

The age of the Zhuangwang 'Formation' andesite (96-PC-114) is 2529 ± 10 Ma and this is considered to be within the lower Shizui 'Subgroup' (Fig. 3). It is virtually identical to the age of the Gaofan 'Subgroup' tuff (95-PC-55c) at 2528 ± 6 Ma, considered to be at the top of the sequence (Tian *et al.* 1996; Ma & Bai 1998). This indicates that: (1) the difference in metamorphic grade between the Zhuangwang 'Formation' (amphibolite facies) and the Gaofan 'Subgroup' (low greenschist facies) has no apparent age significance and cannot be used as a discriminator to map-out stratigraphy (contrast with Bai 1986; Tian 1991; Ma & Bai 1998); (2) the rocks evolved rapidly, so that there is no recognizable stratigraphy to the felsic volcanics at the resolution

Table 4. *Sample numbers, locations, $^{207}Pb/^{206}Pb$ zircon ages and average Th/U ratios of the eight felsic volcanic samples discussed in this study. The 'formations' are listed from top to bottom in the stratigraphic order identified in Bai (1986) and Tian (1991)*

Formation name	Sample no.	Location	Age (Ma)	Th/U Ratio (av.)
Gaofan	95-PC-55c	Lat. 38°56′13″; Long. 113°00′40″	2528 ± 6	0.64
Hongmenyan	WT 17	Lat. 39°02′52″; Long. 113°36′45″	2524 ± 8	0.53
	WT 13	Lat. 39°02′53″; Long. 113°37′13″	2533 ± 8	0.57
	WT 12	Lat. 39°02′49″; Long. 113°36′54″	2516 ± 5	0.61
	WT 9	Lat. 39°02′52″; Long. 113°36′54″	2523 ± 9	0.58
Baizhiyan	96-PC-115	Lat. 39°03′42″; Long. 113°15′60″	2524 ± 10	0.64
Zhuangwang	96-PC-119	Lat. 39°05′19″; Long. 113°16′50″	2513 ± 8	0.69
	96-PC-114	Lat. 39°04′01″; Long. 113°16′38″	2529 ± 10	0.74

of our data and, by implication, to the mafic volcanics and metasediments interleaved with them.

In the two 'formations' where we have analysed more than one sample, there is considerable variation between the ages. In the Zhuangwang 'Formation', sample 96-PC-119 (the most discordant of the samples analysed) has a date of 2513 ± 8 Ma, whereas sample 96-PC-114 has a date of 2529 ± 10 Ma. These just overlap within error, but are at the two extremes of the dates that we have obtained; 2513 ± 8 Ma being the youngest date recorded and 2529 ± 10 Ma being the second oldest (Table 4). Similarly, the spread of dates recorded from the so-called Hongmenyan 'Formation' range from 2516 ± 5 Ma for sample WT 12 (second youngest) to 2533 ± 8 Ma for sample WT 13 (the oldest age obtained from the suite). One possibility is that this may be attributable to an error in the original mapping of the 'formations'. However, samples from the Hongmenyan 'Formation' were all collected from a single, well-exposed 3-km-long traverse and considered to represent a simple stratigraphic sequence on all published maps and by Y. Tian (pers. comm., 1996). As with the data for the units considered to represent the basal and upper 'subgroups' of the sequence (Zhuangwang and Gaofan, respectively), the validity of the individual 'formations' is also severely compromised. The slightly younger age of 2516 ± 5 Ma for sample WT 12 may be real, since the field evidence suggested that it was slightly transgressive and might therefore be a somewhat younger intrusive.

Significance of the results

The new data presented here require revision of the 'stratigraphic model' for the Wutai 'Group' (see also Cawood *et al.* 1998), since the previously accepted stratigraphic divisions are no longer valid. Because the Wutai area has been used to define type-locations for greenstone belt stratigraphy, orogenies and tectonic events (Fig. 2) throughout China (Ma & Bai 1998), this has important ramifications.

Relationship to associated granitoids

A number of granitic intrusions are associated with the Wutai Complex, and field evidence indicates a range of relationships. Many granitoids are strongly deformed and in tectonic contact, so that original contact relations cannot be unequivocally interpreted. Wilde *et al.* (1997) identified that some granitoids were older than the felsic volcanics of the Wutai 'Group' – the Lanzhishan granite new Longquanguan and Ekou granite at Ekou (Fig. 1) having SHRIMP $^{207}Pb/^{206}Pb$ ages of *c.*2545 Ma and 2555 ± 6 Ma, respectively. They also established the younger age of the Dawaliang granite near Gaofan at 2176 ± 12 Ma. Two distinct suites of granitoid have been identified (Wang *et al.* 2000; Liu *et al.* 2002): those older than the Wutai volcanics, including some bodies coeval with the volcanics with ages of 2530–2525 Ma, and a younger set of intrusions (including both the Dawaliang Granite and the pink phase of the Wangjiahui granite southeast of Daixian – Fig. 1) with ages of 2170–2120 Ma.

The Lanzhishan Granite was originally considered to be unconformably overlain by the Wutai Complex (Liu *et al.* 1985). However, we have questioned this interpretation (Wilde *et al.* 1997), considering the granite to be overlain by the Hutuo Group at several localities. Furthermore, its contacts are sheared, like those between the Ekou Granite and the Wutai Complex. Details on the age and relationship of the granitoids to the Wutai Complex will be discussed in a subsequent paper.

Relationship to adjacent terranes

Three main lithotectonic components are recognized in the area: the Wutai, Fuping and Hengshan complexes (Fig. 1). Traditionally, in the Chinese literature, the Wutai Complex has been considered to unconformably overlie both the Fuping and Hengshan complexes (Tian *et al.* 1996). Both the Fuping and Hengshan complexes consist of a variety of grey granitoid gneisses, amphibolites and metasediments at amphibolite- to granulite-facies metamorphic grade (Bai 1986; Tian 1991). The Hutuo Group, which is mostly composed of low-grade metasediments with minor metavolcanics, is considered to be the youngest unit in the region, and to unconformably overlie the Wutai and Fuping Complexes (Tian 1991).

The Wutai Complex was generally considered to have developed within a continental rift environment, due to fracturing of pre-existing continental crust, now represented by the Fuping and Hengshan complexes (Tian 1991). Alternatively, Li, J. *et al.* (1990), Li & Wang (1992) and Sun *et al.* (1992) suggested that plate-tectonic-styled terrane accretion may have occurred, resulting in the collision of a typical low-grade Archaean greenstone sequence (the Wutai Complex), with island-arc affinity, and older continental fragments (the Fuping and Hengshan complexes) during the Late Archaean. The Fuping Complex was considered to be an ancient continental nucleus Liu *et al.* (1985). Sun *et al.* (1992), on the other hand, proposed that it was the basal portion of an island-arc. Li & Wang (1992) further developed the plate-tectonic

model, suggesting that the Fuping Complex formed part of a *c.*2.9 Ga microcontinent which collided with both the Hengshan Complex (another microcontinent) and the Wutai Complex (containing both island-arc and fore-arc components) in the Early Proterozoic (*c.*2.0 Ga). A major shear zone (the Longquanguan Shear Zone) was considered to be the surface expression of a décollement that controlled the thin-skin tectonics of the foreland.

SHRIMP U–Pb zircon geochronology (Guan *et al.* 2002; Zhao *et al.* 2002), has shown that the Fuping Complex is composed of four lithotectonic units: the Fuping gneisses, Longquanguan augen gneisses, Wanzi supracrustals and Nanying granitic gneisses (Zhao *et al.* 2002). Cathodoluminescence (CL) and backscattered electron (BSE) images reveal the coexistence of magmatic and metamorphic zircons in nearly all rock types of the Fuping Complex (Guan *et al.* 2002; Zhao *et al.* 2002). SHRIMP U–Pb analyses on magmatic zircons reveal that the Fuping TTG gneisses were emplaced between 2523 ± 14 Ma and 2486 ± 8 Ma ago (Guan *et al.* 2002; Zhao *et al.* 2002), whereas the protoliths of the Longquanguan augen gneisses were intruded between 2543 ± 7 Ma and 2507 ± 11 Ma (Wilde *et al.* 1997; Zhao *et al.* 2002). SHRIMP data also reveal that the Nanying granitic gneisses formed between 2077 ± 13 Ma and 2024 ± 21 Ma (Guan *et al.* 2002; Zhao *et al.* 2002). Zircon grains and new overgrowth zircon rims from all components of the Fuping Complex yielded similar concordant $^{207}Pb/^{206}Pb$ dates in the range 1875–1802 Ma, interpreted as approximating the age of regional metamorphism of the Fuping Complex (Guan *et al.* 2002; Zhao *et al.* 2002). In addition, Guan *et al.* (2002) obtained a SHRIMP U–Pb zircon age of 2708 ± 8 Ma for a hornblende gneiss, which occurs as enclaves in the Fuping gneisses. Work on the Hengshan Complex (Kroner *et al.* 2001; Zhao *et al.* 2001a) has shown a similar range of ages to those recorded from the Fuping Complex. In both areas, the preferred interpretation is that they represent lower components of a complex arc system, of which the Wutai Complex represents the upper portion (Fig. 6), and which was assembled into its current position at *c.*1.8 Ga (see also Zhao *et al.* 2001b; Wilde *et al.* 2002). No components older than *c.*2.7 Ga have so far been identified in either the Fuping or Hengshan Complexes. Indeed, the majority of rocks are similar in age to the Wutai Complex; this implies that neither the rift model (Tian 1991) nor the plate-tectonic model of Li & Wang (1992), involving older cratonic blocks, is viable.

Tectonic setting

Zhao *et al.* (2000 & 2001*b*) have proposed that Wutaishan and the adjacent Fuping and Hengshan complexes (Fig. 1), lie within the Central Zone of the North China Craton. This zone, also referred to as the Trans-North China Orogen (Zhao *et al.* 2001a), is a linear zone of crustal thickening characterized by clockwise P–T paths, which separates two major crustal blocks–referred to as the eastern and western blocks (Zhao *et al.* 1998), that are considered to be separate continental nuclei which collided at *c.*1.8 Ga ago (Zhao *et al.* 2001b; Wilde *et al.* 2002). The western block consists of Archaean tonalite–trondhjemite–granodiorite (TTG) gneisses and mafic igneous rocks, unconformably overlain by Palaeoproterozoic high-grade metasedimentary rocks referred to locally as 'khondalites' (Zhao *et al.* 1999). The Archaean rocks underwent greenschist- to granulite-facies metamorphism at 2.6–2.5 Ga and are characterized by anticlockwise P–T paths. The eastern block also consists of TTG gneisses, accompanied by syntectonic granitoids and interleaved supracrustal rocks, including ultramafic to felsic volcanic rocks and metasediments, metamorphosed from greenschist to granulite facies; also exhibiting anticlockwise P–T paths (Zhao *et al.* 2001b). In contrast to the western block, some basement rocks have considerably older protolith ages, up to *c.*3.8 Ga (Song *et al.* 1996).

Our new results are important on the craton-scale, for the following reasons. The age data from felsic volcanic rocks in the Wutai Complex suggest a single magmatic source that extended over a period of approximately 20 Ma, from *c.*2533 to *c.*2515 Ma, with a mean age of 2523 ± 3 Ma. Because there is no difference in the age of the felsic volcanic rocks within the Wutai Complex, these findings may also apply equally to other associated components of the complex, with the proviso that some younger rocks of the Hutou Group might be interleaved (Cawood *et al.* 1998). The complex had previously been considered an unconformity-bounded, layer-cake stratigraphic succession up to 5 km thick (Tian *et al.* 1996) that was either formed in a rift environment (Tian 1991) or island-arc setting (Li J. *et al.* 1990; Li & Wang 1992). Both models imply that the Wutai rocks were younger than the adjacent Fuping and Hengshan complexes, which is not supported by our new data.

Investigations of the Wutai Complex (Wilde & Wang 1995; Wilde *et al.* 1997, 1998 and 2001; Wang *et al.* in press) have established that this complex represents relicts of an island and/or

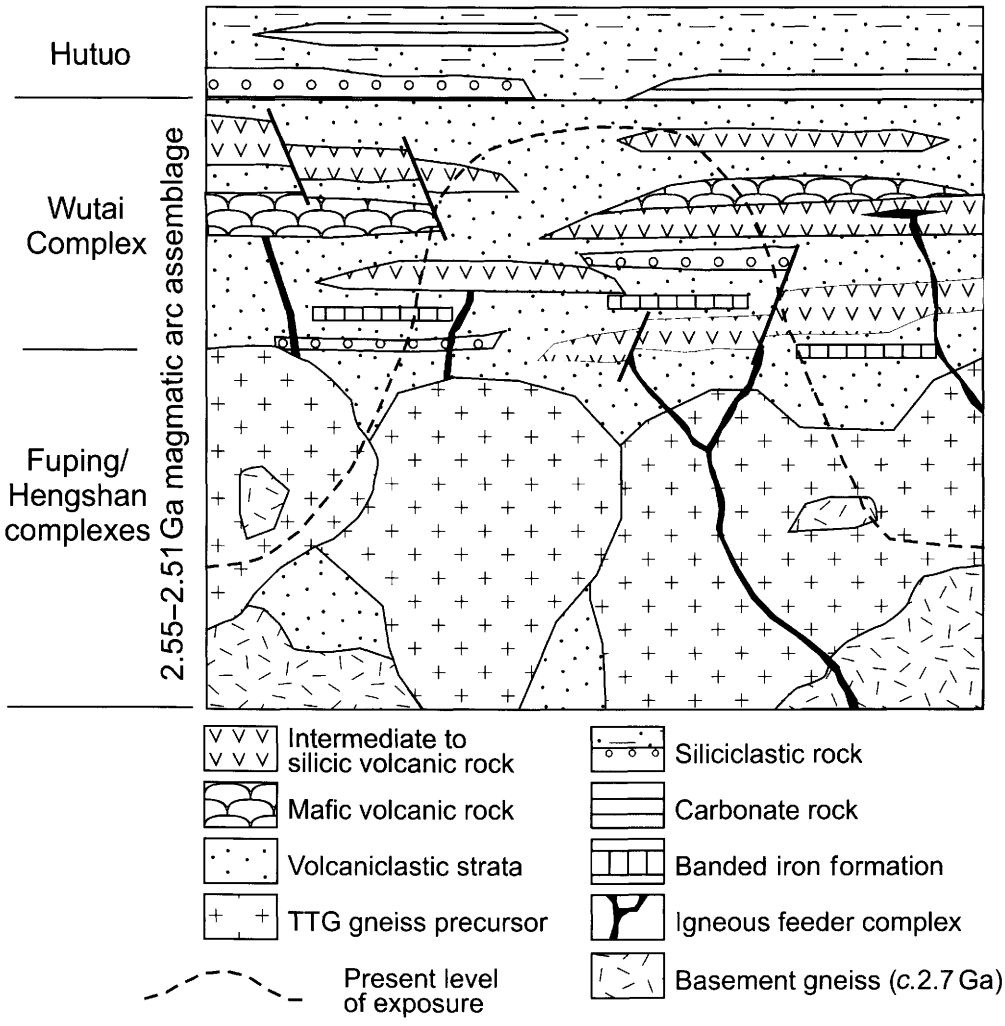

Fig. 6. Schematic diagram showing the relationship of the major lithological components within the Wutai arc system prior to dismemberment at 1.8 Ga. Approximate width of diagram is 75 km.

magmatic arc composed of mafic, intermediate and felsic volcanic rocks, with associated volcaniclastic and chemical sediments (Fig. 6). We consider that the components of the arc have been tectonically disrupted during a major collisional event and interleaved with granitoids, some of which predate the volcanic rocks and others which evolved coevally with them (Wilde *et al.* 1997; Wang *et al.* 2000). Our present results further substantiate this interpretation, with the implication of repetition of the sequence rather than a true stratigraphy.

With respect to the timing of deformation and metamorphism, geochronological evidence shows that metamorphic ages of *c.*1800 Ma are present throughout the area, especially in the higher-grade rocks. This age was originally considered to represent a local thermal event (Tian 1991; Bai *et al.* 1992). However, since all three crustal complexes show evidence of major tectonothermal activity at this time, the event is of regional extent. Evidence includes K–Ar data on hornblendes from the low-grade Wutai Complex of 1782 ± 20 Ma (Wang *et al.* 1997) and metamorphic overgrowths on existing zircons and generation of new zircons in rocks of the higher-grade Hengshan and Fuping Complexes at *c.*1.8 Ga (Kroner *et al.* 2000; Guan *et al.* 2002; Zhao *et al.* 2001a). It now appears that the *c.*1.8 Ga event (the so-called Lüliang

orogeny) records the timing of collision resulting from amalgamation of the east and west blocks of the North China Craton and its formation as a crustal entity (see also Zhao *et al.* 2001b; Wilde *et al.* 2002).

Our new data indicate that, in one sample (96-PC-115), a $^{207}Pb/^{206}Pb$ date of 2679 ± 16 Ma (Fig. 4c) was recorded from two of three older, inherited zircons. This is the only volcanic sample to contain inheritance, and this in turn suggests that at least some of the components of the Wutai Complex were extruded through pre-existing crust (Fig. 6). It has previously been noted (Wilde *et al.* 1997) that some of the earlier granitoids at Wutaishan also contain inherited zircons as old as *c.*2.7 Ga, considered to most likely represent components of the eastern block of the North China Craton (Wilde *et al.* 2002); a similar origin is proposed for the older zircons contained in the Wutai volcanics, and this suggests that part of the Wutai Complex might also have evolved at the western continental margin of the eastern block.

Locally, tonalitic gneisses as old as *c.*2.7 Ga are also present in the Fuping (Guan *et al.* 2002) and Hengshan (Kroner *et al.* 2001) complexes. Therefore, not only are the dominant rock-types in the Wutai, Fuping and Hengshan Complexes 2.52 Ga old, but all three areas contain evidence of earlier *c.*2.7-Ga crustal components.

Geochemical data (Sun *et al.* 1992; Liu *et al.* in press) support the view that the high-grade granitic gneisses of the Fuping and Hengshan Complexes are arc-related. Because of their similarity in age (Guan *et al.* 2002; Zhao *et al.* 2001b) and chemistry (Liu *et al.* in press; Wang *et al.* in press) to the Wutai Complex, they may represent part of the same arc system (Kroner *et al.* 2001; Wilde *et al.* 2002). We therefore interpret both the Hengshan and Fuping Complexes as the lower part of a Late Archaean arc complex (Fig. 6), with the intervening Wutai Complex representing the upper portion of the arc (Kroner *et al.* 2001; Zhao *et al.* 2001b; Guan *et al.* 2002; Wilde *et al.* 2002; Zhao *et al.* 2002). It appears likely that the arc may have been complex, since it contains island-arc and back-arc components (Wang *et al.* in press), as well as segments that erupted through pre-existing continental crust.

At the present time, there are insufficient data to adequately model the convergent margin components of the arc, or to elucidate the full sequence of events that occurred between arc formation at 2.53 Ga – possibly along the western margin of the eastern block of the North China Craton – and collision with the western block at *c.*1.8 Ga (Zhao *et al.* 2001b). One possibility is that the island-arc/back-arc components amalgamated with the western margin of the eastern block during the late Archaean/earliest Proterozoic and subsequently evolved as a passive margin. The age of the overlying Hutuo Group at $2366 +103/-94$ Ma (Wu *et al.* 1986) is poorly constrained, although it may be a correlative of the *c.*2100 Ma Wanzi Supracrustal Suite that is tectonically interleaved with the Fuping TTG gneisses (Guan *et al.* 2002). There is also a suite of younger granitoids with Palaeoproterozoic ages of *c.*2150 Ma in the Wutai, Fuping and Hengshan Complexes (Wilde *et al.* 1997; Guan *et al.* 2002). These data suggest that the complexes had a common evolution from *c.*2.2 Ga.

Our favoured interpretation, therefore, is that the Wutai, Fuping and Hengshan Complexes evolved at a convergent margin along the western continental margin of the Eastern block of the North China Craton (Zhao *et al.* 2001b; Wilde *et al.* 2002). They were subsequently tectonically dismembered, interleaved with Palaeoproterozoic shelf sediments and granitoids and metamorphosed at *c.*1.8 Ga during a major collision that brought together the eastern and western blocks of the North China Craton (Zhao *et al.* 2001*b*; Wilde *et al.* 2002).

Conclusions

New SHRIMP U–Pb data from felsic volcanic rocks collected throughout the Wutai sequence in the North China Craton establish that:

(1) The rocks have similar dates within error, indicating that there is only one period of volcanism recorded in the Wutai Complex. This shows a range in age from 2533 ± 8 Ma to 2513 ± 8 Ma, with a mean of 2523 ± 3 Ma.

(2) There is no layer-cake stratigraphy to the Wutai Complex and, coupled with evidence of structural complexity, this indicates that the rocks are tectonically juxtaposed. Remapping of this classic area of Chinese geology will probably reveal a complex tectonostratigraphy.

(3) There is no correlation between metamorphic grade and age of volcanic rocks in the Wutai Complex, contrary to previous views (Bai 1986; Tian 1991; Tian *et al.* 1996).

(4) There is a similarity in age between the igneous rocks of the low-grade Wutai Complex and those in the high-grade Fuping and Hengshan complexes (Guan *et al.* 2002; Kroner *et al.* 2001; Zhao *et al.* 2001b). There is also a consistency in the geochemical data (Sun *et al.* 1992; Wang *et al.* in press), tending to support a common origin within a complex arc system.

(5) There is no evidence for rocks older than *c.*2.7 Ga in any of the three complexes and there

is thus no apparent difference between the so-called Fuping and Wutai 'movements' or orogenic events. Furthermore, there is no direct evidence that the Wutai or Fuping/Hengshan complexes were deformed prior to *c.*1.8 Ga ago (Kroner *et al.* 2001), and so the very existence of the Fuping and Wutai orogenies is in need of re-evaluation.

(6) The marked similarity in age between the main metamorphic events in the Wutai, Fuping and Hengshan Complexes at *c.*1800 Ma indicates that the Lüliang 'movement' (orogeny) is the major tectonic event in the region. It resulted in formation of the North China Craton by amalgamation during collision of the eastern and western blocks (Zhao *et al.* 2000).

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