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2006

CURRENT RESEARCH

Natural Resources Canada
Ressources naturelles Canada

Canada

ISSN 1701-4387
Catalogue No. M44-2006/A3E-PDF
ISBN 0-662-42826-9

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Publication approved by GSC Pacific, Vancouver

Original manuscript submitted: 2005-12-12
Final version approved for publication: 2006-02-02

Correction date:

Overview of the volcanology of the Bell-Irving volcanic district, northwestern Bowser Basin, British Columbia: new examples of mafic alpine glaciovolcanism from the northern Cordilleran volcanic province

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Edwards, B.R., Evenchick, C.A., McNicoll, V.J., Wetherell, K., and Nogier, M., 2006: Overview of the volcanology of the Bell-Irving volcanic district, northwestern Bowser Basin, British Columbia: new examples of mafic alpine glaciovolcanism from the northern Cordilleran volcanic province; Geological Survey of Canada, Current Research 2006-A3, 12 p.

Abstract: Fourteen previously undescribed volcanic occurrences were documented from the west-central Bowser Basin, in northern British Columbia, and have been assigned to the Bell-Irving volcanic district. Thirteen of the areas were briefly surveyed during aerial reconnaissance, while the fourteenth was mapped and described during three days of fieldwork in August of 2004. All fourteen areas contained deposits of pillow lavas and/or volcaniclastic rocks and were interpreted as products of Pleistocene, alpine glaciovolcanic eruptions. Samples from Craven Lake volcanic centre are basanites. A sample from the Bell-Irving River volcanic centre was dated by ^{40}Ar-^{39}Ar to be 0.43 ± 0.15 Ma, consistent with the interpretation that the deposits formed via interaction with Pleistocene ice. The Bell-Irving volcanic district is considered to be part of the northern Cordilleran volcanic province.

Résumé : Quatorze occurrences de roches volcaniques, non décrites jusqu'à présent, ont été reconnues dans la partie centrale ouest du bassin de Bowser, dans le nord de la Colombie-Britannique, et sont attribuées au district volcanique de Bell-Irving. Treize de ces régions ont été examinées brièvement dans le cadre d'un levé aérien de reconnaissance, alors que la quatorzième région a été cartographiée et décrite en août 2004 lors de trois jours de travaux sur le terrain. Les 14 régions renferment des laves en coussins ou des roches volcanoclastiques qui, selon notre interprétation, sont des produits d'éruptions glaciovolcaniques alpines au Pléistocène. Des échantillons provenant du centre volcanique de Craven Lake sont des basanites. La datation $^{40}Ar/^{39}Ar$ d'un échantillon provenant du centre volcanique de Bell-Irving River donne un âge de $0,43 \pm 0,15$ Ma, ce qui est compatible avec l'interprétation selon laquelle les dépôts se seraient formés par interaction avec la glace pléistocène. Le district volcanique de Bell-Irving est considéré comme faisant partie de la province volcanique du nord de la Cordillère.

INTRODUCTION

Overview

The results described herein derive from work conducted during the summers of 2002 and 2004 and are an indirect result of the 'Integrated Petroleum Resource Potential and Geoscience Studies of the Bowser and Sustut Basins' collaboration between the British Columbia Ministry of Energy and Mines and the Geological Survey of Canada. While mapping Jurassic to Cretaceous rocks of the Bowser Lake Group east of the second crossing (from the south) of Highway 37 over the Bell-Irving River (Fig. 1), volcanic deposits were discovered along several ridge tops (*see* Fig. 2 *in* Evenchick et al., 2005). The largest and most accessible deposit, immediately north of Craven Lake (Fig. 1), was chosen for detailed mapping and sampling during three days of fieldwork in August 2004. This report presents an overview of the aerial survey as well as preliminary results from the detailed work near Craven Lake. Mineralogical and geochemical studies of lava and xenolith samples from Craven Lake are underway at Dickinson College.

Pertinent Regional Geology

The Bowser Basin is a Jurassic to Cretaceous clastic sedimentary basin that comprises, in the area of interest, sedimentary rocks of the Bowser Lake Group (Fig. 2 *in* Evenchick et al., 2005). The Bowser Lake Group includes the Ritchie-Alger assemblage in the western part of the map area, the Groundhog-Gunanoot assemblage in the northeastern part of the map area, and the Muskaboo Creek assemblage in the southeast (Evenchick et al., 2005). Younger volcanic deposits overlie the Bowser Lake Group in a number of areas (Fig. 1).

The newly mapped volcanic deposits are herein referred to as the Bell-Irving volcanic district and share many characteristics with neighbouring northern Cordilleran volcanic province (NCVP; Edwards and Russell, 2000) centres, including close spatial proximity, similar inferred ages (Pleistocene), similar eruptive environments (glaciovolcanic),

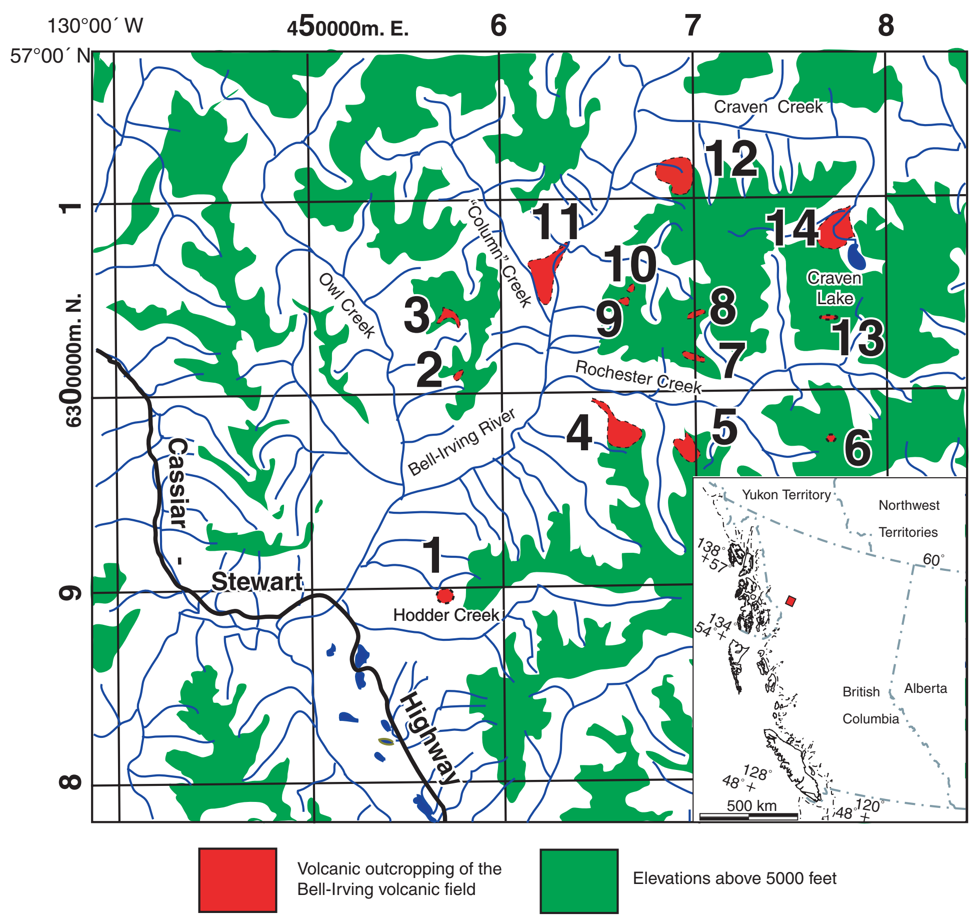

Figure 1. Map showing locations within the Bell-Irving volcanic district in the northwestern corner of NTS map sheet 104 A. *See* Table 1 for names corresponding to numbers. Inset map shows approximate location of figure within British Columbia (North American datum 1927).

and similar mineralogies. Neogene to Recent volcanic centres and deposits from the NCVP occur to the north (Pliocene Maitland volcanic complex, Souther and Yorath, 1991; Evenchick and Thorkelson, 2005), northwest (Edziza volcanic complex, Souther, 1992), west (Iskut volcanic field, Russell and Hauksdottir, 2000; Hoodoo volcanic complex, Edwards et al., 2002), and south (Nass volcanic district; Evenchick and Mustard, 1996) of the Bell-Irving volcanic district (Fig. 2). The NCVP comprises predominantly mafic alkaline volcanic rocks and includes many examples of glaciovolcanic deposits (Mathews, 1947; Allen et al., 1982; Moore et al., 1995; Simpson, 1996; Edwards and Russell, 2002).

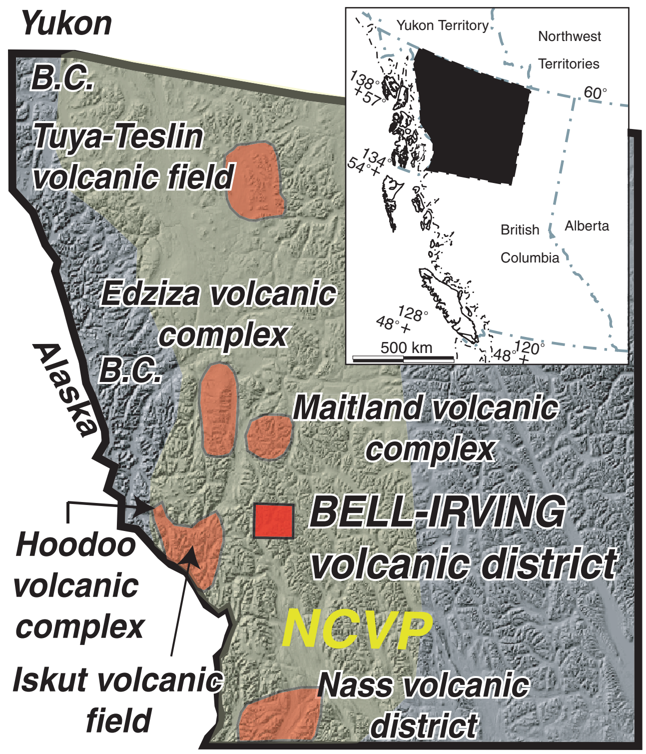

Figure 2. Location of the Bell-Irving volcanic district with respect to other northern Cordillera volcanic province (NCVP) volcanoes. The NCVP in northwestern British Columbia is shown in light yellow; the Edziza volcanic complex, the Iskut volcanic field, and the Tuya-Teslin volcanic field are shown in light red; the Bell-Irving volcanic district as a bright red rectangle (British Columbia hillshade image by K. Shimamura based on 1:50 000 Digital Elevation Models obtained from Geobase). Inset map shows approximate location of figure within British Columbia.

RESULTS OF AERIAL SURVEY OF VOLCANIC DEPOSITS

Initial recognition of isolated volcanic outcrops was made during field work in 1992, 2002, and follow up work was completed in 2004. Previously, at least two of the volcanic deposits, Bell-Irving River and Craven Lake, had been mapped at the reconnaissance level (Wheeler and McFeeley, 1991). An additional three outcrops were described and delineated in regional mapping (Evenchick et al., 1992; 2000), but were assumed to be part of the Pliocene Maitland Volcanics. So far, 14 isolated occurrences of volcanic rocks have been identified, and preliminary aerial reconnaissance has been made to inventory the locations and types of volcanic deposits present at each of the occurrences (Table 1). At present, each occurrence has been given an informal geographic name for ease of referral within the text. Where an eruptive vent is inferred based on morphology or presence of abundant dykes, the location is referred to as a 'volcanic centre'; otherwise the location is referred to as a 'volcanic deposit', indicating that it may be an erosional remnant at some distance from the eruptive vent. This preliminary classification is expected to change as more-detailed assessments are made for each of the locations. Reported minimum apparent deposit thicknesses are approximate and are based on comparisons of outcrop photographs and topography. Most deposits appear to have experienced variable amounts of post-depositional erosion.

Table 1. Summary of locations and field observations of deposits and volcanic centres within the Bell-Irving volcanic district (co-ordinates in NAD27).

Informal name of volcanic deposit / centre	UTM for centre of deposit	Maximum elevation (in feet above sea level)
1. Adzich	455000 E / 6289000 N	4500
2. Owl Creek S	457900 E / 6301100 N	5500
3. Owl Creek N	457250 E / 6304100 N	5700
4. Rochester Creek SW	466750 E / 6297500 N	5700
5. Rochester Creek SE	469500 E / 6297500 N	5000
6. Upper Rochester Creek	477500 E / 6297500 N	5000
7. Rochester Creek NES	469750 E / 6301600 N	5800
8. Rochester Creek NEN	469100 E / 6303500 N	6100
9. Bell-Irving River ES	466400 E / 6304750 N	6612
10. Bell-Irving River EN	466750 E / 6305400 N	6000
11. Bell-Irving River	462100 E / 6306250 N	3600
12. Bell Irving NE	470000 E / 6310100 N	5000
13. Icefield Ridge	477300 E / 6340000 N	6100
14. Craven Lake	477500 E / 6307500 N	5000

1. Adzich volcanic centre

The volcanic deposits are exposed sporadically on top of a heavily forested ridge approximately 5 km northeast of the mouth of Hodder Creek (Table 1; Fig. 1, 3). Exposures are poor, but appear to comprise mainly orange-weathering volcanic breccia with rare interbedded pillow lavas.

The centre forms a conical hill, with a basal diameter of about 0.5 km and a minimum apparent thickness of approximately 150 m.

2. Owl Creek South volcanic deposits

The volcanic deposits are exposed along the top of a southwesterly trending alpine ridge located approximately 7.5 km north of the junction of Owl Creek and the Bell-Irving River (Table 1; Fig. 1, 4). The deposits comprise mostly coarse- and fine-grained volcanic breccia. The fine-grained breccia weathers to a distinctly orange colour, appears to be well-lithified, and is cut by dykes. The deposits are exposed along approximately 500 m of the ridgeline and have a minimum apparent thickness of about 60 m.

Figure 3. Aerial view looking southwest at the forested Adzich volcanic centre (Photograph EP040272), marking the west-central edge of the Bell-Irving volcanic district. Hillock is approximately 100 m high.

3. Owl Creek North volcanic deposits

The volcanic deposits are exposed on a small peak and two ridges branching from the peak, located approximately 9 km north of the junction of Owl Creek and the Bell-Irving River (Table 1; Fig. 1, 4). Similar to the Rochester Creek SE and SW, and the Bell-Irving NE centres, the centre has been cut by glacial cirques and hence the highest outcroppings now form a pyramid-shaped mound near the summit. The ridges extend for about 0.9 km to the southwest and 1.1 km to the southeast of the summit. Most of the outcrops comprise pillow lavas, many of which are cut by dykes estimated to be less than 5 m wide and small, pipe-like structures with curved jointing patterns that are interpreted as intrusions. The minimum apparent thickness of the deposits is approximately 180 m.

4. Rochester Creek Southwest (SW) volcanic centre

The volcanic deposits are exposed mainly on two ridges on the south side of Rochester Creek approximately 5 km east southeast of its junction with the Bell-Irving River (Table 1; Fig. 1, 5). The centre comprises a relatively thick sequence including pillow lavas near the top of the ridges and orange volcaniclastic deposits downslope. Grey, layered volcaniclastic deposits also outcrop downslope to the north and west from the main ridge at elevations of 5800 ft. to elevations of

Figure 4. Aerial view looking northwest at Owl Creek S (foreground) and Owl Creek N (background) volcanic deposits (photograph EP040179), both of which are outlined by white dashed lines. The Owl Creek S deposit is approximately 500 m long.

Figure 5. Aerial view looking southwest at Rochester Creek SW volcanic centre (photograph EP040509), which is outlined by a white dashed line. The ridge is approximately 2 km long from the highest point to the lower edge of the white dashed line.

approximately 3000 ft. The minimum apparent thickness for the deposits is about 500 m, and they are spread over a west-southwest-trending elongate area about 1.5 by 2.5 km.

5. Rochester Creek Southeast (SE) volcanic centre

Volcanic deposits are exposed along a ridge above the southern side of Rochester Creek, directly west of the Rochester Creek SW centre (Table 1; Fig. 1, 6); the centre is 7.5 km to 8.5 km east southeast of the junction of Rochester Creek and the Bell-Irving River. The deposits cap two northwesterly sloping narrow ridges bounding a glacial cirque, and therefore form a horseshoe map pattern, with the longest arm more than 2.5 km long; the base of the deposits dips northwest (Fig. 6). The deposits comprise volcanic breccia, some of which appears to be layered, and pillow lava; both unconformably overlie steeply dipping Bowser Lake Group strata (Fig. 6). The centre is distinctive in its abundance of dykes cutting the volcanic breccia deposits near the highest elevations (Fig. 6). The range of elevation spanned by the deposits is about 730 m, with an estimated minimum apparent thickness of approximately 100 m.

6. Upper Rochester Creek volcanic deposits

An outcrop about 150 m long and 70 m wide of volcanic breccia is exposed along a ridge at an elevation of 6500 ft., 15.1 km east of the junction of Rochester Creek and the Bell-Irving River (Fig. 1). The range of elevation spanned by the deposits is less than 40 m and the deposit has an estimated minimum thickness of 30 m.

7. Rochester Creek Northeast-South (NES) volcanic deposits

The volcanic deposits are exposed along a ridge for approximately 1.1 km that trends slightly south of east, on the northern side of Rochester Creek (Table 1; Fig. 1, 7). The deposits comprise mainly isolated pillow-lava tubes and volcanic breccia. The range of elevation spanned by the deposits is approximately 150 m, with an estimated minimum apparent thickness of less than 70 m. It appears to have been deposited on a steep south-southwest-facing slope approximately parallel with the Rochester Creek valley.

8. Rochester Creek Northeast-North (NEN) volcanic deposits

The volcanic deposits are exposed for approximately 0.5 km along a narrow, alpine ridge elongated southwest-northeast, approximately 8.5 km east northeast of the junction of Rochester Creek and the Bell-Irving River (Table 1; Fig. 1, 8). The deposits comprise dark-brown- and rusty-weathering pillow lava and volcanic breccia, and light yellow, bedded volcaniclastic deposits containing clasts of xenoliths. The range of elevation spanned by the deposits is approximately 120 m, with an estimated minimum apparent thickness of about 100 m.

9. and 10. Bell-Irving River East South (ES) and East North (EN) volcanic deposits

The volcanic deposits form two separate exposures along a northeast-trending ridge (Bell-Irving ES and EN; Table 1; Fig. 1, 9). The northern, lower elevation exposure (EN), is

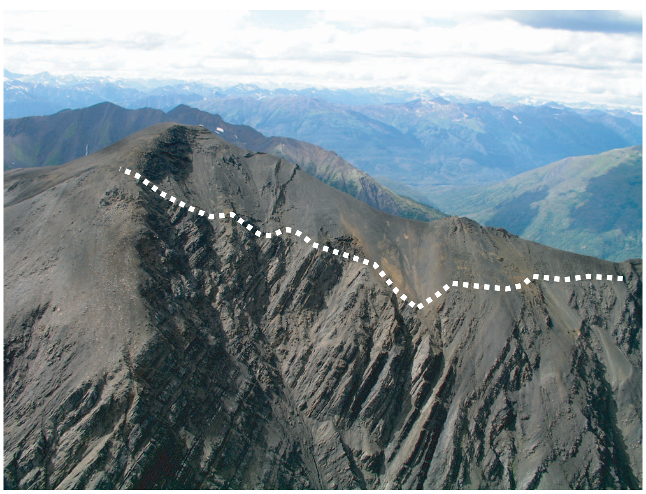

Figure 6. Aerial view looking northwest at summit of the Rochester Creek SE volcanic centre (photograph EP040501). Volcanic deposits on the summit are cut by younger dykes and unconformably overlie near-vertical Bowser Lake Group units. The contact between the volcanic deposit and underlying Bowser Lake Group is marked by the dashed white line. The vertical distance from the contact to the ridgetop is approximately 100 m.

Figure 7. Aerial view looking north at Rochester Creek NES volcanic deposit (photograph EP040260). The contact between the volcanic deposit and underlying Bowser Lake Group is marked by the dashed white line. The deposits outcrop for approximately 1.1 km along the ridge top.

Figure 8. Aerial view looking north at Rochester Creek NEN volcanic deposit (photograph EP040256). The contact between the volcanic deposit and underlying Bowser Lake Group is marked by the dashed white line. The deposits outcrop for approximately 0.5 km along the ridge top.

Figure 9. Aerial view looking east at Bell-Irving East (S) volcanic deposit showing volcanic units unconformably overlying folded Bowser Lake group sedimentary rocks (photograph EP040477). The contact between the volcanic deposit and underlying Bowser Lake Group is marked by the dashed white line. The deposits outcrop for approximately 250 m along the ridge top.

approximately 250 m long and 180 m wide, forms a spectacular unconformity overlying an anticline of Bowser Lake group sedimentary rocks (Fig. 9), and weathers -dark orange. The outcrop comprises volcanic breccia interbedded with pillow lava and chaotically oriented, columnar-jointed bodies interpreted as dykes. The southern, upper exposure (ES) is about 500 m long and comprises a basal, white-yellow coloured unit and darker yellow, well bedded volcaniclastic deposits. The range of elevation spanned by the two deposits combined is approximately 250 m, with an estimated minimum apparent thickness of about 50 m.

11. Bell-Irving River volcanic centre

The deposits form a pyramid-shaped hill along the western side of the Bell-Irving River (Fig. 1, 10) approximately 17 km east northeast of the junction of Bell-Irving River and Owl Creek. The western edge of the volcanic deposits are exposed along the east side of a creek, herein referred to as 'Column' creek, and the eastern edge of the deposits are exposed along the western side of the Bell-Irving River (Table 1; Fig. 1, 10). The former exposures include a columnar-jointed pillar greater than 50 m in height, which has white vein fillings on some joint surfaces. The pillar directly overlies Bowser Lake Group conglomerate (Fig. 11). Most of the other exposures comprise dark orange volcanic breccia and finer grained volcaniclastic deposits. Isolated outcrops on the northeast, above Bell-Irving River, appear to have pillow-lava structures (Fig. 12). The range of elevation spanned by the deposits is about 330 m, with an estimated minimum apparent thickness of approximately 330 m.

12. Bell-Irving Northeast (NE) volcanic deposits

The volcanic deposits form a pyramid-shaped landform along a northerly trending ridgeline approximately 4.5 km southeast of the junction of Craven Creek and the Bell-Irving River (Table 1; Fig. 1, 13). The deposits comprise possibly two separate stratigraphic sets of pillow lava and are crosscut by dykes. The range of elevation spanned by the deposits is about 700 m, with an estimated minimum apparent thickness of approximately 180 m. The base of the deposit slopes steeply to the northwest into the Bell-Irving River valley. Volcanic breccia varies in colour from orange at high elevations to gray at low elevations. The change in colour may indicate different degrees of palagonitization of vitric fragments.

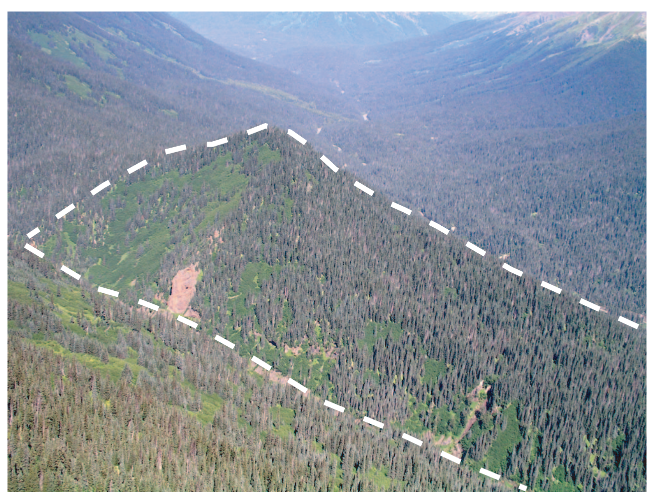

Figure 10. Aerial view looking northeast up the Bell-Irving River valley at Bell-Irving River volcanic centre (photograph EP040201). Hillock formed by the volcanic deposits is approximately 330 m in height.

Figure 11. Aerial view looking east at a spire of columnar-jointed lava directly above Bowser Lake Group conglomerate along the western edge of the Bell-Irving River volcanic centre (photograph EP040013). The vertical field of view is approximately 30 m.

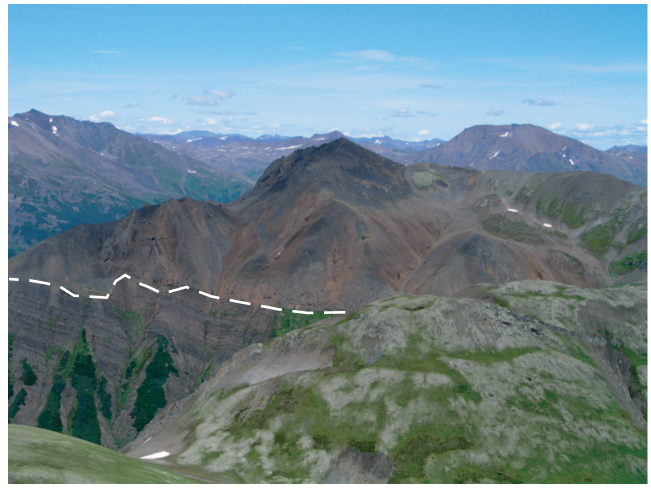

Figure 13. Aerial view looking east at Bell-Irving East volcanic centre (photograph EP040208). Vertical height from white dashed line to dark-coloured peak is ca. 180 m.

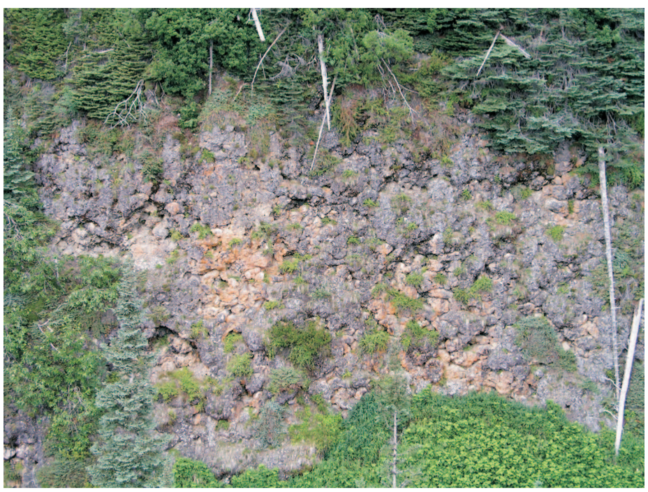

Figure 12. Aerial view looking northwest at Bell-Irving River volcanic centre (photograph EP040020), showing a sequence of pillow lava approximately 25 m thick.

Figure 14. Aerial view looking east at Craven Lake volcanic centre with Craven Lake in the background (EP040240). Horizontal distance from the top of the volcanic centre to the left edge of the field of view is approximately 2 km.

13. Icefield Ridge volcanic deposit

The deposits form the top of an east-west-trending narrow ridge, approximately 700 m long and up to 200 m wide (Table 1; Fig. 1). The deposits comprise volcanic breccia and have a maximum thickness of approximately 70 m.

14. Craven Lake volcanic centre

The volcanic deposits immediately northwest of the outlet of Craven Lake (Table 1; Fig. 1, 14) were visited on two separate occasions, including three days to complete a preliminary outcrop map and collect approximately 50 samples for petrological studies that are currently in progress. The deposits were mapped to the top of a ridge west of the outlet of Craven Lake and along stream cuts above Craven Creek for approximately 3 km northwest of the lake. The deposits comprise pillow lava (Fig. 15) and massive lava in addition to volcaniclastic deposits. The uppermost slopes comprise three types of deposits, in order of decreasing abundance: unconsolidated ash and lapilli, massive pillow lava, and consolidated ash and lapilli. Along the ridge, which extends downhill to the east, are isolated outcrops of pillow lava and consolidated ash and lapilli. The range of elevation spanned by the deposits is about 540 m, with an estimated minimum apparent thickness of approximately 330 m.

Figure 15. Pillow lava exposed along Craven Creek immediately northwest of the outlet to Craven Lake (photograph EP040104).

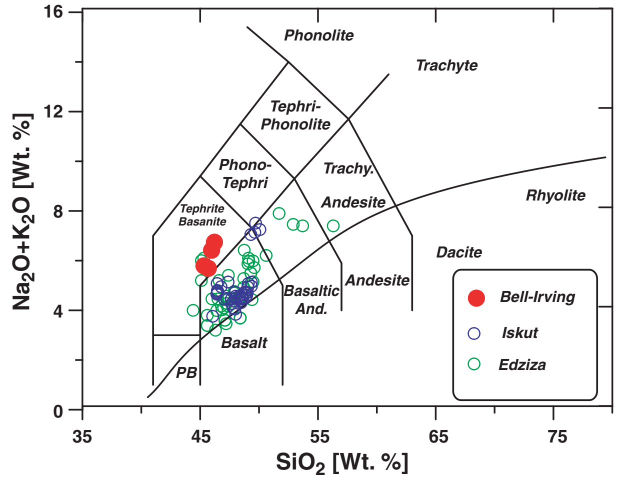

Figure 16. Total alkalies versus silica diagram (fields from LeBas et al., 1986) showing the compositions of four samples from the Craven Lake volcanic centre. Also shown are samples from the Iskut volcanic field (Russell and Hauksdottir, 2000) and the Mount Edziza volcanic complex (Souther, 1992).

Geochemically, the rocks are basanites (Fig. 16) and have phenocrysts of olivine-plagioclase-clinopyroxene. The rocks have a more alkaline signature than basaltic rocks from the nearby Iskut volcanic field and the Mount Edziza volcanic complex (Fig. 16). A variety of feldspathic and peridotitic xenoliths are present in the lavas and in the volcaniclastic rocks (Fig. 17), as are plagioclase and clinopyroxene megacrysts.

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

Laser $^{40}Ar/^{39}Ar$ step-heating analysis was carried out at the Geological Survey of Canada (GSC) with data collection protocols *after* Villeneuve and MacIntyre (1997) and Villeneuve et al. (2000), and error analysis following Scaillet (2000) and Roddick (1988). Analytical data are presented in Table 2, and plotted in Figure 18. Further details on the $^{40}Ar/^{39}Ar$ analytical techniques are presented in Appendix 1. The sample location is noted in Table 2.

Analysis was carried out on four aliquots of whole-rock fragments from volcanic sample EP-04-99A from the Bell-Irving volcanic centre (laboratory sample number z8393; Fig. 18). The sample has a nearly constant Ca/K ratio throughout most of the heating process, with the exception of the last steps of all four aliquots, which may indicate slight degassing of another phase (Fig. 18a). All four aliquots yield a plateau region; however, excess argon is apparent in the early steps of each aliquot (Fig. 18a). An inverse isochron of all the data from the four analyzed aliquots yields an age of 0.43 ± 0.15 Ma (MSWD = 1.4) (Fig. 18b). The inverse isochron plot shows some scatter as a result of a mixture of excess argon and atmosphere, especially in the first heating steps. The more radiogenic steps show less scatter. The $^{40}Ar/^{36}Ar$ intercept value of 301 ± 1.4 is outside error of

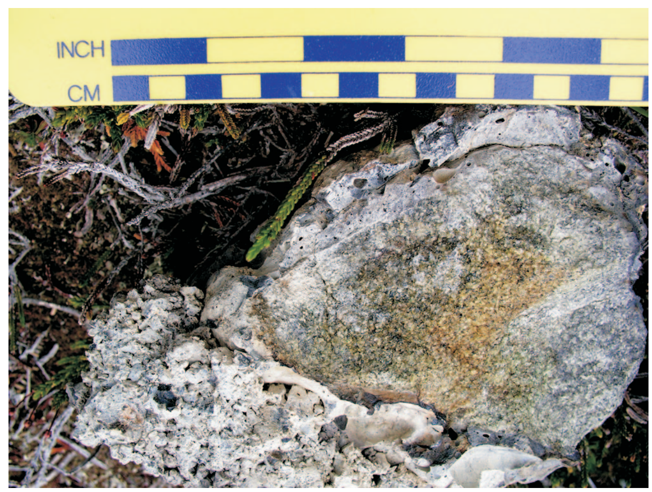

Figure 17. Peridotite xenolith from Craven Lake volcanic centre (photograph EP040112).

atmospheric air, which has a value of 295.5, also revealing the presence of some excess argon. The date of 0.43 ± 0.15 Ma is interpreted to be the crystallization age of the rock.

ONGOING RESEARCH WITHIN THE BELL-IRVING VOLCANIC DISTRICT

Although a few of the Bell-Irving volcanic centres were demarcated during previous regional mapping, no descriptions exist for any of the 14 volcanic centres documented herein. Several important issues relating to the volcanology and petrology of the Bell-Irving volcanic district are currently

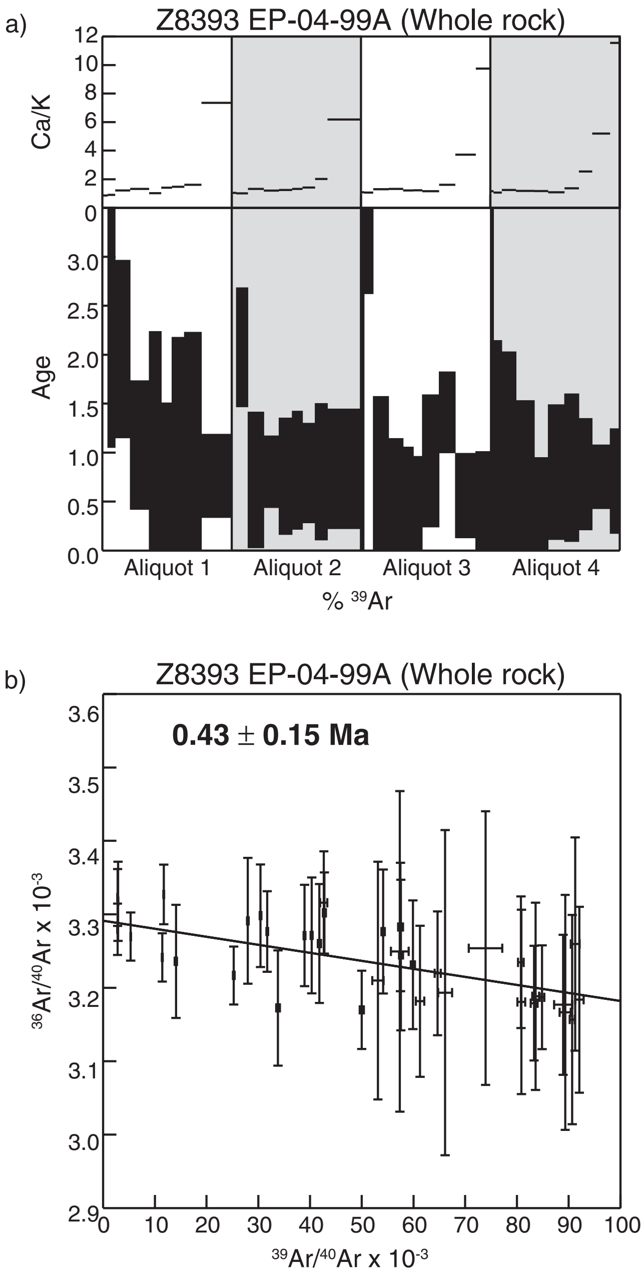

Figure 18. Plots showing $^{40}Ar/^{39}Ar$ data for sample EP-04-99A from the Bell-Irving River volcanic centre. A) Gas-release spectrum containing step-heating data and Ca/K ratios from 4 aliquots. B) Inverse-isochron diagram containing all 4 aliquots, with an interpreted age of 0.43 ± 0.15 Ma.

being addressed or will be in the near future, including basic xenolith and lava-sample petrology, centre-specific stratigraphic studies, and investigations on the eruptive environments for the district as a whole. Petrological, mineralogical, and geothermometric studies are currently underway at Dickinson College on ultramafic xenoliths from the Craven Lake centre.

The presence of pillow lavas at elevations well above sea level is consistent with the majority of the 14 centres having been erupted in glaciovolcanic environments. All of the centres also appear to be mafic, based on the weathering characteristics of the deposits. The ongoing detailed mineralogical and geochemical studies of the peridotite xenoliths will provide critical information about the composition of the lithospheric mantle beneath the Bowser Basin. As well, all of the deposits have experienced at least some degree of geomorphic modification by alpine glaciation. Radiometric studies presented herein confirm that at least one of the deposits is Pleistocene.

Many of the deposits are near the highest elevations of the region, and basal contacts slope into two of the modern major river valleys, the Bell-Irving River and Rochester Creek. The highest elevation deposits are in upper Rochester Creek, at 6700 ft. (2042 m). The lowest elevation deposits are in the Bell-Irving River valley at 2500 ft. (760 m), only 200 ft. (60 m) above the valley floor and only 4 km to the west of the Bell-Irving East deposits at 6600 ft. (2010 m). Such field relationships are consistent with the interpretation that the Bell-Irving and Rochester drainages were well established during the Pleistocene.

SUMMARY

Fourteen new volcanic occurrences are now recognized in the northwestern part of the Bowser Basin and have been assigned to the Bell-Irving volcanic district. All deposits are assumed to be Pleistocene and appear to be glaciovolcanic in origin; a sample from the Bell-Irving volcanic centre yielded an age of 0.43 +/- 0.15 Ma. Hand-sample and geochemical analyses indicate that the Craven Lake volcanic centre comprises basanitic-composition volcanic rocks. The Bell-Irving volcanic district is considered to be part of the northern Cordilleran volcanic province (Edwards and Russell, 2000).

ACKNOWLEDGEMENTS

Thanks to Darrell Adzich (Canadian Helicopters) for safe helicopter travel and sharp eyes for spotting volcanic deposits, and to Dickinson College for start-up funds for B.E. to conduct the fieldwork, and to the Research and Development Committee for a 2004 Faculty-Student Research Grant to support summer research by K.W. and M.N. Nancy Joyce and Mike Villeneuve are thanked for their assistance in generating the argon data. Thanks also to K. Shimamura (Geological Survey of Canada) for providing a digital version of the British Columbia shaded relief map used as a base for Fig. 2, and to K. Simpson (Geological Survey of Canada) for an insightful review of the manuscript.

Table 2: Ar/Ar data for sample EP-04-99A from the Bell-Irving River volcanic centre.

Power[a]	Volume ^{39}Ar x10^{-11} cc	^{36}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{38}Ar/^{39}Ar	^{40}Ar/^{39}Ar	%^{40}Ar ATM	*^{40}Ar/^{39}Ar	f_{39}[b] (%)	Apparent age (Ma)[c]
EP-04-99A Whole rock; J = 0.00071040 (Z8393; UTM zone 9 NAD 27, 461170E-6304953N)									
Aliquot 1									
2.4	0.3616	1.1923 ± 0.0201	0.453 ± 0.020	0.014 ± 0.014	360.166 ± 4.757	97.8	7.832 ± 3.828	0.5	10.01 ± 4.88
2.8	0.5194	0.2322 ± 0.0063	0.469 ± 0.014	0.014 ± 0.011	71.115 ± 1.072	96.5	2.490 ± 1.670	0.8	3.19 ± 2.14
3.0	1.0225	0.0947 ± 0.0023	0.631 ± 0.016	0.007 ± 0.011	29.590 ± 0.300	94.6	1.607 ± 0.709	1.5	2.06 ± 0.91
3.5	1.3012	0.0524 ± 0.0017	0.686 ± 0.012	0.007 ± 0.011	16.320 ± 0.220	94.9	0.840 ± 0.513	1.9	1.08 ± 0.66
3.9	0.8378	0.0487 ± 0.0033	0.536 ± 0.009	0.008 ± 0.011	15.123 ± 0.306	95.2	0.725 ± 1.022	1.2	0.93 ± 1.31
4.2	0.7286	0.0444 ± 0.0018	0.736 ± 0.014	0.009 ± 0.011	13.526 ± 0.591	97.0	0.400 ± 0.778	1.1	0.51 ± 1.00
5.0	0.8637	0.0572 ± 0.0036	0.762 ± 0.016	0.007 ± 0.011	17.427 ± 0.520	96.9	0.538 ± 1.163	1.2	0.69 ± 1.49
6.0	1.1643	0.0609 ± 0.0030	0.844 ± 0.020	0.009 ± 0.011	18.816 ± 0.392	95.7	0.809 ± 0.933	1.7	1.04 ± 1.20
13.0	2.0913	0.0360 ± 0.0009	3.824 ± 0.036	0.006 ± 0.011	11.245 ± 0.221	94.7	0.596 ± 0.332	3	0.76 ± 0.43
Aliquot 2									
2.4	0.6516	0.6207 ± 0.0083	0.545 ± 0.017	0.005 ± 0.012	188.075 ± 1.661	97.5	4.663 ± 1.879	0.9	5.97 ± 2.40
2.8	1.6446	0.1286 ± 0.0018	0.529 ± 0.010	0.011 ± 0.011	39.631 ± 0.268	95.9	1.619 ± 0.476	2.4	2.07 ± 0.61
3.0	2.2053	0.0569 ± 0.0018	0.688 ± 0.009	0.007 ± 0.011	17.365 ± 0.117	96.8	0.563 ± 0.542	3.2	0.72 ± 0.69
3.5	2.1639	0.0385 ± 0.0010	0.626 ± 0.012	0.006 ± 0.011	12.002 ± 0.097	94.8	0.628 ± 0.286	3.1	0.80 ± 0.37
3.9	1.8627	0.0385 ± 0.0016	0.650 ± 0.009	0.007 ± 0.011	11.961 ± 0.097	95.1	0.592 ± 0.464	2.7	0.76 ± 0.60
4.2	1.4910	0.0397 ± 0.0016	0.690 ± 0.017	0.008 ± 0.011	12.366 ± 0.115	94.8	0.641 ± 0.472	2.2	0.82 ± 0.61
5.0	1.7377	0.0502 ± 0.0014	0.745 ± 0.016	0.007 ± 0.011	15.463 ± 0.139	96.0	0.618 ± 0.397	2.5	0.79 ± 0.51
6.0	1.7638	0.0358 ± 0.0019	1.051 ± 0.014	0.010 ± 0.011	11.195 ± 0.135	94.4	0.628 ± 0.545	2.5	0.81 ± 0.70
13.0	4.7256	0.0351 ± 0.0016	3.223 ± 0.023	0.007 ± 0.011	11.028 ± 0.058	94.1	0.652 ± 0.478	6.8	0.83 ± 0.61
Aliquot 3									
2.4	0.4466	1.1978 ± 0.0201	0.563 ± 0.018	0.012 ± 0.014	357.022 ± 4.351	99.1	3.071 ± 4.210	0.6	3.93 ± 5.38
2.8	1.3211	0.2863 ± 0.0035	0.561 ± 0.010	0.009 ± 0.011	87.535 ± 0.637	96.7	2.923 ± 0.876	1.9	3.74 ± 1.12
3.0	2.2067	0.1095 ± 0.0024	0.681 ± 0.013	0.011 ± 0.011	32.885 ± 0.184	98.4	0.530 ± 0.699	3.2	0.68 ± 0.90
3.5	2.1006	0.0611 ± 0.0016	0.690 ± 0.012	0.009 ± 0.011	18.466 ± 0.116	97.7	0.419 ± 0.474	3	0.54 ± 0.61
3.9	1.4847	0.0576 ± 0.0016	0.636 ± 0.009	0.012 ± 0.011	17.390 ± 0.144	97.9	0.362 ± 0.463	2.1	0.46 ± 0.59
4.2	1.2996	0.0784 ± 0.0020	0.643 ± 0.014	0.009 ± 0.011	23.427 ± 0.381	98.9	0.252 ± 0.499	1.9	0.32 ± 0.64
5.0	2.4241	0.1043 ± 0.0018	0.601 ± 0.008	0.005 ± 0.011	31.525 ± 0.168	97.7	0.714 ± 0.527	3.5	0.92 ± 0.68
6.0	2.3414	0.0639 ± 0.0012	0.839 ± 0.010	0.006 ± 0.011	19.997 ± 0.159	94.5	1.102 ± 0.324	3.4	1.41 ± 0.42
7.0	2.9476	0.0404 ± 0.0011	1.941 ± 0.019	0.006 ± 0.011	12.380 ± 0.086	96.5	0.438 ± 0.337	4.3	0.56 ± 0.43
13.0	2.0977	0.0360 ± 0.0016	5.066 ± 0.044	0.008 ± 0.011	10.957 ± 0.102	97.2	0.305 ± 0.483	3	0.39 ± 0.62
Aliquot 4									
2.4	0.5945	1.1698 ± 0.0259	0.604 ± 0.022	0.005 ± 0.012	349.235 ± 5.179	99.0	3.552 ± 5.731	0.9	4.55 ± 7.33
2.8	1.4974	0.2865 ± 0.0040	0.555 ± 0.011	0.010 ± 0.011	85.277 ± 0.605	99.3	0.624 ± 1.051	2.2	0.80 ± 1.35
3.0	2.6041	0.1188 ± 0.0032	0.650 ± 0.008	0.010 ± 0.011	35.761 ± 0.207	98.2	0.652 ± 0.931	3.8	0.84 ± 1.19
3.5	3.3270	0.0819 ± 0.0020	0.620 ± 0.008	0.005 ± 0.011	24.791 ± 0.111	97.6	0.602 ± 0.595	4.8	0.77 ± 0.76
3.9	2.5013	0.0779 ± 0.0014	0.609 ± 0.011	0.009 ± 0.011	23.362 ± 0.153	98.5	0.350 ± 0.392	3.6	0.45 ± 0.50
4.6	2.9895	0.0848 ± 0.0018	0.565 ± 0.008	0.007 ± 0.011	25.671 ± 0.123	97.6	0.625 ± 0.539	4.3	0.80 ± 0.69
5.5	2.6178	0.0787 ± 0.0021	0.711 ± 0.010	0.010 ± 0.011	23.907 ± 0.183	97.2	0.661 ± 0.589	3.8	0.85 ± 0.76
6.5	2.4032	0.0544 ± 0.0015	1.323 ± 0.016	0.006 ± 0.011	16.698 ± 0.113	96.4	0.608 ± 0.445	3.5	0.78 ± 0.57
7.5	3.2632	0.0379 ± 0.0009	2.704 ± 0.021	0.006 ± 0.011	11.784 ± 0.064	95.0	0.588 ± 0.254	4.7	0.75 ± 0.33
13.0	1.7719	0.0349 ± 0.0014	6.006 ± 0.057	0.007 ± 0.011	10.862 ± 0.098	94.9	0.553 ± 0.419	2.6	0.71 ± 0.54

a: As measured by laser in % of full nominal power (10 W)

b: Fraction ^{39}Ar as percent of total run

c: Errors are analytical only and do not reflect error in irradiation parameter J

d: Nominal J, referenced to FCT sanidine = 28.03 Ma (Renne et al., 1994)

All uncertainties quoted at 2σ level

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APPENDIX

$^{40}Ar/^{39}Ar$ Analytical Techniques

The sample was processed for $^{40}Ar/^{39}Ar$ analysis of whole-rock fragments by standard mineral-separation techniques, including hand-picking of clear, unaltered rock fragments in the 0.25 to 0.5 mm size range. The whole-rock fragments were loaded into aluminum foil packets along with Fish Canyon Tuff sanidine to act as flux monitor (apparent age of 28.03 ± 0.1 Ma; Renne et al., 1994). The sample packets were arranged radially inside an aluminum can. The samples were then irradiated for 2 hours at a power of 3 MW at the research reactor of McMaster University in a fast neutron flux of approximately $3x10^{16}$ neutrons/cm^2.

Laser $^{40}Ar/^{39}Ar$ step-heating analysis was carried out at the Geological Survey of Canada laboratories in Ottawa, Ontario. Upon return from the reactor, the sample was split into several aliquots and loaded into individual 1.5 mm diameter holes in a copper planchet. The planchet was then placed in the extraction line and the system evacuated. Heating of individual sample aliquots in steps of increasing temperature was achieved using a Merchantek MIR10 10W CO_2 laser equipped with a 2 mm x 2 mm flat-field lens. The released Ar gas was cleaned over getters for ten minutes, and then analyzed isotopically using the secondary electron multiplier system of a VG3600 gas-source mass spectrometer; details of data collection protocols can be found in Villeneuve and MacIntyre (1997) and Villeneuve et al. (2000). Error analysis on individual steps follows numerical error analysis routines outlined in Scaillet (2000); error analysis on grouped data follows algebraic methods of Roddick (1988).

Corrected argon isotopic data are listed in Table 2, and presented as spectra of gas release and additionally on an inverse-isochron plot (Fig. 18; Roddick et al. 1980). The gas-release spectrum plotted contains step-heating data from four aliquots, alternately shaded and normalized to the total volume of ^{39}Ar released. Such plots provide a visual image of replicated heating profiles and the error and apparent age of each step. The inverse-isochron plot contains all of the data from the four analyzed aliquots.

Neutron flux gradients throughout the sample canister were evaluated by analyzing the sanidine flux monitors included with each sample packet and interpolating a linear fit against calculated J-factor and sample position. The error on individual J-factor values is conservatively estimated at ± 0.6% (2 sigma). Because the error associated with the J-factor is systematic and not related to individual analyses, correction for this uncertainty is not applied until calculation of dates from isotopic correlation diagrams (Roddick, 1988). All errors are quoted at the 2 sigma level of uncertainty.