Evidence for a late Cambrian juvenile arc and a buried suture within the Laurentian Caledonides of Scotland: comparisons with hyper-extended Iapetan margins in the Appalachians and Norway

M. Dunk[1], R.A. Strachan[1], K.A. Cutts[2], S. Lasalle[1], C.D. Storey[1], I.M. Burns[3], M.J. Whitehouse[4], M. Fowler[1] H. Moreira[1], J. Dunlop[1] & I. Pereira[1]

1. School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Rd, Portsmouth, PO1 3QL.

2. Department of Geology, Universidad Federal de Ouro Preto, Ouro Preto, Brazil.

3. 6, McKenzie Crescent, Bettyhill, By Thurso, Sutherland, KW14 7SY

4. Department of Geosciences, Swedish Museum of Natural History, Box 50 007, SE-104 05, Stockholm, Sweden.

ABSTRACT

U-Pb zircon dating establishes a late Cambrian (Drumian) protolith age of 503 ± 2 Ma for a trondhjemitic gneiss of the calc-alkaline Strathy Complex, northern Scottish Caledonides. Positive εHf and εNd values from trondhjemitic gneisses and co-magmatic amphibolites respectively, and an absence of any inheritance in zircon populations, support published geochemistry that indicates a juvenile origin distal from Laurentia. In order to account for its present location within a stack of Laurentia-derived thrust sheets, we interpret the complex as allochthonous and located along a buried suture. We propose that a microcontinental ribbon was detached from Laurentia during late Neoproterozoic to Cambrian rifting; the intervening oceanic tract closed by subduction during the late Cambrian and formed a juvenile arc, the protolith of the Strathy Complex. The microcontinental ribbon was re-attached to Laurentia during the Grampian orogeny which transported the Strathy Complex as a tectonic slice within a nappe stack. Peak metamorphic conditions for the Strathy Complex arc (650-700˚C, 6-7.5 kbar) are intermediate in pressure between those published previously for Grampian mineral assemblages in structurally overlying low-P migmatites (670-750˚C, <4 kbar) which we deduce to have been derived from an adjacent back-arc basin, and structurally underlying upper amphibolite rocks (650-700˚C, 11-12 kbar) that we interpret to represent the partially subducted Laurentian margin. This scenario compares with the northern Appalachians and Norway where microcontinental terranes are interpreted to have their

origins in detachment from passive margins of the Iapetus Ocean during Cambrian rifting and to have been re-amalgamated during Caledonian orogenesis.

INTRODUCTION

The identification of suture zones in orogens depends upon the recognition of indicators of convergent plate margin processes such as calc-alkaline igneous rocks, high-pressure/low-temperature metamorphic rocksand ophiolites. The complexity of many orogens may be inherited from a prior history of continental break-up as rifted margins can be characterized by hyper-extension and detached continental ribbons (e.g. North Atlantic Ocean; Péron-Pinvidic and Manatschal, 2010). Subsequent ocean closure by subduction of the intervening oceanic tracts typically results in a collage of terranes separated by sutures (Vink et al., 1984). However, identification of sutures is challenging where tectonic excision has removed indicators of subduction, or where these have been buried either tectonically or beneath successor basins.

The Appalachian-Caledonide orogen (Fig. 1A) contains a record of Neoproterozoic to Early Cambrian rifting and continental break-up prior to the opening of the Iapetus Ocean. During rifting along the length of the Appalachians (Laurentia) and Norway (Baltica), it has been interpreted that continental ribbons were detached from craton margins and re-accreted during Ordovician-Silurian orogenesis (Waldron and van Staal, 2001; Hibbard et al., 2007; Andersen et al., 2012). In NW Ireland, the granulite facies Slishwood Division may represent a Laurentian fragment that was detached during rifting and later partially subducted (Daly et al., 2012). In Scotland, the orogenic architecture has been interpreted more simply with the Highland Boundary Fault apparently separating Laurentia from oceanic terranes (Fig. 1A; Chew and Strachan, 2013). To the northwest are exposedLaurentian Neoproterozoic metasedimentary successions, whereas to the southeast the Midland Valley Terrane is underlain by oceanic arcs (Dewey and Ryan, 1990), and the Southern Uplands Terrane comprises an accretionary prism (Leggett et al., 1979; Stone, 2014). In NW Scotland (Fig. 1B), the meta-igneous Strathy Complex has been interpreted as a calc-alkaline arc and regarded as basement to the Tonian Moine Supergroup (Moorhouse and Moorhouse, 1983; Burns et al., 2004). New data instead establish a late Cambrian protolith age and, together with published field and geochemical data, require that the complex is allochthonous and defines a cryptic suture. Our new tectonic model for the northern Scottish Caledonides proposes an early evolution that has more in common with the Appalachians and Norway than supposed previously.

STRUCTURAL SETTING AND GEOLOGY OF THE STRATHY COMPLEX

The Caledonides of northern Scotland comprises a series of thrust sheets that are dominated by the Moine Supergroup and associated Archean basement (Strachan et al. 2010; Fig. 1B). Thrusting occurred during the closure of the Iapetus Ocean and the Silurian (Scandian) collision of Laurentia and Baltica (Fig. 1B; Strachan et al. 2010). The Hebridean foreland to the west comprises Archean basement (Lewisian Complex) with a cover of Mesoproterozoic and Cambrian–Ordovician strata. Imbricated Cambrian strata in the footwall of the Moine Thrust restore to an outcrop width of >50 km which represents the minimum eastern extent of the Hebridean foreland at depth (Butler and Coward, 1984) .

The Moine Supergroup was metamorphosed during the Neoproterozoic (Strachan et al. 2010) but the peak metamorphic assemblages in the Naver and Swordly nappes (Fig. 1B) were formed during Ordovician (Grampian) arc-continent collision (Kinny et al., 1999; Friend et al., 2000). The Strathy Complex occupies an anticlinal fold core (Fig. 1B; Moorhouse and Moorhouse, 1983). Its western boundary with overlying Moine rocks of the Swordly Nappe is interpreted as a folded ductile thrust (Port Mor Thrust, Fig. 1B). The main ductile structures within the Naver and Swordly nappes and the Strathy Complex are assigned to the Grampian orogeny; late upright folding (Fig. 1B) occurred during Scandian thrusting (Kinny et al., 1999, 2003; Burns et al., 2004).

The Strathy Complex comprises a bimodal association of trondhjemitic grey gneisses and amphibolites with rare ultramafic lithologies, garnet-staurolite-sillimanite paragneiss and marble (Moorhouse and Moorhouse, 1983; Burns et al., 2004). The grey gneisses and amphibolites have calc-alkaline chemistry (Moorhouse and Moorhouse, 1983; Burns et al., 2004). Geochemical evidence indicates that the mafic end-member (amphibolites) was derived from a depleted mantle source and may have been related by crystal fractionation to the trondhjemitic grey gneisses (Burns et al., 2004). δ^{18}O values of whole rock samples and mineral separates, and their correlations with major and trace elements suggest that the protoliths were hydrothermally altered at <200°C (Burns et al., 2004), consistent with the igneous protoliths being extrusive (Moorhouse and Moorhouse, 1983) and/or high-level intrusions. The combination of moderate mantle-normalized LILE concentrations (e.g. MORB-normalized Rb and Ba averages of 16 and 15 respectively), flat chondrite-normalized LREE and HREE, pronounced negative Nb anomalies, and positive εNd (+7.0, +6.6, +6.5 and +4.5 at 500 Ma) in basalt-andesite compositions, suggests an origin either as a young intra-oceanic arc or an incipient back-arc (Burns et al., 2004; Schmidt and Jagoutz, 2017; details provided in GSA Data Repository). The rare layers of paragneiss and marble are lithologically dissimilar to any Moine units and here thought to represent relics of a sedimentary carapace to the arc. In the absence of protolith crystallisation ages, it has been assumed to represent a local Paleoproterozoic (Harrison and Moorhouse, 1976) or Mesoproterozoic (Burns et al., 2004) basement to the Moine Supergroup.

NEW ISOTOPIC CONSTRAINTS ON THE STRATHY COMPLEX

Geochronology was carried out by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) on a sample of trondhjemitic gneiss (sample RS-14-16) and three late-kinematic pegmatites (details provided in GSA Data Repository). Twenty-six of 46 U-Pb zircon analyses from RS-14-16 are <15% discordant, with ages ranging from 522 Ma to 383 Ma. Eleven analyses form a cluster giving a Concordia age of 502.7 ± 1.9 Ma (Fig. 2; see supplementary information for a full discussion). The grains dated generally have sector or oscillatory zoning and are interpreted as igneous in origin. The Concordia age is therefore considered to correspond to the crystallisation age of the igneous protoliths of the Strathy Complex arc. Importantly, there is no evidence of any significantly older zircon grains in this sample. The zircons that were used to calculate the Concordia age have $^{176}Hf/^{177}Hf$ ratios that correspond to εHf values of +6 to +10.

None of the pegmatites analysed yielded a Concordia age. Analyses ranged from c. 463 Ma to c. 411 Ma. Our interpretation is that the pegmatites were produced by melting of host gneisses during the Grampian orogeny at c. 470 Ma at the same time as Moine rocks of the Swordly Nappe were migmatized (Kinny et al., 1999). The zircon analyses are therefore interpreted as reflecting lead loss and variable resetting during the Scandian orogenic event. U-Pb monazite dating carried out on sample RS-14-16 yielded a Concordia age of 422.1 ± 2.8 Ma. U-Pb rutile dating carried out on a sample of garnet-staurolite-sillimanite paragneiss (MD-16-01) yielded a Concordia age of 433 ± 5 Ma. The monazite and rutile ages are within error of a monazite age of 431 ± 10 Ma obtained from nearby Moine rocks above the Swordly Thrust (Kinny et al., 1999) and are also interpreted as dating reheating during Silurian thrusting.

NEW METAMORPHIC CONSTRAINTS ON THE EARLY HISTORY OF THE STRATHY COMPLEX

Detailed thermobarometric analysis was carried out on the garnet-staurolite-sillimanite paragneiss (MD-16-01). The sample was obtained from a 6 x 2 m boudin enclosed within grey gneiss. The mineral assemblage associated with the early, sub-vertical gneissic foliation within the boudin is retrogressed at its margins. The boudin is wrapped by a subhorizontal foliation that is interpreted to have formed during the Grampian orogeny at the same time as regional migmatisation of the Moine rocks of the Swordly Nappe (Kinny et al., 1999). This locality therefore provides a unique opportunity to ascertain the early peak metamorphic conditions of the Strathy Complex during the

Grampian orogeny. Pressure-temperature pseudosections were calculated for sample MD-16-01 using THERMOCALC V.3.33 (June 2009 update of Powell and Holland, 1988) in the geologically realistic system MnNCKFMASHTO (MnO-Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3) (see also GSA Data Repository). The peak assemblage is interpreted to be garnet + orthoamphibole + sillimanite + biotite + plagioclase + quartz + rutile, corresponding to 650–700 °C and 6–7.5 kbars (Fig. 3). The prograde pressure-temperature (*P-T*) path is defined by the change of mineral assemblage and the growth of garnet. On a *P-T* (Fig. 3) the peak metamorphic conditions lie intermediate in pressure between those for Grampian mineral assemblages in overlying migmatites of the Swordly Nappe dated at 461 ± 13 Ma (670–750˚C, <4 kbar; Kinny et al., 1999) and underlying upper amphibolite to granulite facies rocks (650–700˚C, 11–12 kbar) of the Naver Nappe (Friend et al., 2000). All three *P-T* boxes are interpreted to be Grampian in age and are distinctly different from the peak conditions deduced for the Naver Nappe during Scandian thrusting and folding (Fig. 3; ca. 730˚C and 9 kbar; Ashley et al., 2015).

DISCUSSION

The late Cambrian protolith age for the Strathy Complex shows that it is not part of the basement to the Moine Supergroup. The intervening Port Mor Thrust must be a major tectonic break because: 1) the geochemistry of the Strathy Complex is consistent with hydrothermal alteration of volcanics or shallow intrusives; this chemistry is peculiar to the complex and absent from structurally overlying Moine units; 2) the minor marble and garnet-staurolite-sillimanite paragneiss units are unlike any local Moine or Archean lithologies and are likely to be Cambrian or early Ordovician in age and to have been deposited within or proximal to the arc; 3) the early Grampian metamorphic evolution of the Strathy Complex is different from that of overlying Moine units. Furthermore, we suggest that the complex rests on an unexposed tectonic break which corresponds to a cryptic suture (Fig. 1B). This explains the geochemical and isotopic characteristics of the complex, and the absence of any inherited Proterozoic or Archaean zircon grains in the trondhjemitic gneiss and felsic pegmatites derived from that gneiss, which all imply a juvenile origin in a setting distal from the Laurentian margin. The Strathy Complex appears to have no relation to adjacent rock units and we interpret it as a thrust-bounded terrane.

Our model for the early evolution of the Scottish Caledonides envisages detachment of a fragment of Laurentia during continental rifting at ca. 600–580 Ma (Fig. 4A). This fragment corresponds to the Moine rocks and Archean basement above the Naver Thrust and equivalent structures further south, and the northeastern extension of the Grampian Terrane (Fig. 1A). During the late Cambrian, east-dipping (present reference frame) subduction zones and juvenile magmatic arcs developed on both sides of the microcontinental fragment: to the east the Midland Valley arc (Dewey and Ryan, 1990), and to the west the Strathy Complex arc (Fig. 4B). Arc-continent collisions during the early Ordovician at ca. 480–470 Ma resulted in re-attachment of the microcontinent to Laurentia by thrusting which transported a tectonic slice of the Strathy Complex within a Grampian nappe stack (Fig. 4C). An alternative scenario is that the Strathy Complex represents a far-travelled thrust sheet of the Midland Valley arc that was interleaved with Moine units during later thrusting. However, this is is rejected on the basis that the low-pressure metamorphic conditions in the Swordly Nappe are inconsistent with a location in the footwall of a major thrust sheet.

Our tectonic model explains the juxtaposition of the contrasting Grampian peak metamorphic assemblages. Partial subduction of the leading edge of Laurentia accounts for the *P-T* conditions in the Naver Nappe (Fig. 4C). In contrast, the early *P-T* path for the Strathy Complex is interpreted to have been driven in part by addition of magma into a progressively thickening arc, whereas we suggest that the high temperatures necessary for generation of the Swordly Nappe migmatites were initiated by high heat flow in a back-arc (Fig. 4B; see Hyndman et al., 2005). It is interpreted that initial thrust stacking (Fig. 4C) was followed by extrusion of the Naver Nappe rocks back up the subduction channel, and extensional displacement along the thrusted contact between the Strathy Complex and the Swordly Nappe migmatites, which juxtaposed these contrasting metamorphic terrains at a similar crustal level by the end of the Grampian orogeny (Fig. 4D).

Our tectonic model compares with those for other areas of the Appalachian-Caledonide orogen. In Newfoundland, Waldron and van Staal (2001) proposed detachment of the Dashwoods terrane from the Laurentian passive margin during Cambrian rifting, followed by re-amalgamation in the early Ordovician. A peri-Laurentian continental ribbon terrane was likely present along much of the length of the Appalachians (Hibbard et al., 2007). Our proposal that the Strathy Complex is located along a cryptic buried suture suggests that the northern Scottish Caledonides comprise at least two peri-Laurentian terranes and is therefore more complex in its crustal architecture than considered previously. The evidence for a cryptic suture has largely been buried tectonically, demonstrating the potential difficulties in identifying such structures in ancient orogens.

ACKNOWLEDGEMENTS

The authors thank Fernando Corfu, Daniel Viete and John Waldron for useful reviews and Mark Witton for drafting.

REFERENCES CITED

Andersen, T.B., Corfu, F., Labrousse, L., and Osmundsen, P.T., 2012, Evidence for hyperextension along the pre-Caledonian margin of Baltica: Journal of the Geological Society, London, v. 169, p. 601-612, doi: 10.1144/0016-76492012-011.

Ashley, K.T., Thigpen, J.R., and Law, R.D., 2015, Prograde evolution of the Scottish Caledonides and tectonic implications: Lithos, v, 224-225, p. 160-178, doi: 10.1016/j.lithos.2015.03.011.

Burns, I.M., Fowler, M.B., Strachan, R.A., and Greenwood, P.B., 2004, Geochemistry, petrogenesis and structural setting of the meta-igneous Strathy Complex: a unique basement block within the Scottish Caledonides?: Geological Magazine, v. 141, p. 209-223, doi: 10.1017/S0016756804009070.

Butler, R.W.H., and Coward, M.P., 1984, Geological constraints, structural evolution and the deep geology of the NW Scottish Caledonides: Tectonics, v. 3, p. 347-365, doi: 10.1029/TC003i003p00347.

Chew, D., and Strachan, R.A, 2013, The Laurentian Caledonides of Scotland and Ireland, *in* Corfu, F., Gasser, D., & Chew, D., eds., Current Controversies in the Scandinavian Caledonides: Geological Society, London, Special Publications 390, p. 45-91, doi: dx.doi.org/10.1144/SP390.16.

Dallmeyer, R.D., Strachan, R.A., Rogers, G., Watt, G.R. & Friend, C.R.L., 2001, Dating deformation and cooling in the Caledonian thrust nappes of north Sutherland, Scotland: insights from ^{40}Ar/^{39}Ar and Rb—Sr chronology: Journal of the Geological Society, London, 158, 501-512, doi: 10.1144/jgs.158.3.501.

Daly, J.S., Flowerdew, M.J., and Whitehouse, M.J., 2012, Grampian high-pressure granulite-facies metamorphism of the Slishwood Division, NW Ireland, and its enigmatic eclogite-facies precursor: Abstract, European Geophysical Union, General Assembly, 22-24 April 2012, Vienna, p. 13462.

Dewey, J.F., and Ryan, P.D., 1990, The Ordovician evolution of the South Mayo Trough, western Ireland: Tectonics, v. 9, p. 887-903, doi: 10.1029/TC009i004p00887.

Friend, C.R.L., Jones, K.A., and Burns, I.M., 2000, New high-pressure granulite facies event in the Moine Supergroup, northern Scotland: implications for Taconic (early Caledonian) crustal Evolution: Geology, v. 28, p. 543-546, doi: 10.1130/0091-7613(2000)28<543:NHGEIT>2.0.CO;2.

Harrison, V.E., and Moorhouse, S.J., 1976, A possible early Scourian supracrustal assemblage within the Moine: Journal of the Geological Society, London, v. 132, p. 461-466., doi: 10.1144/gsjgs.132.4.0461.

Hibbard, J.P., van Staal, C.R., and Rankin, D.W., 2007, A comparative analysis of pre-Silurian crustal building blocks of the northern Appalachian and the southern Appalachian orogen: American Journal of Science, v. 307, p. 23-45, doi: 10.2475/01.2007.02.

Holland, T.J.B., and Powell, R., 1998, An internally consistent thermodynamic data set for phases of petrological interest: Journal of Metamorphic Geology, v. 16, p. 309-334, doi: 10.1111/j.1525-1314.1998.00140.x.

Hyndman, R.D., Currie, C.A., and Mazzotti, S., 2005, Subduction zone backarcs, mobile belts, and orogenic heat: GSA Today, v. 15, p. 4-10, doi: 10.1130/1052-5173(2005)015<4:SZBMBA>2.0.CO;2.

Kinny, P.D., Friend, C.R.L., Strachan, R.A., Watt, G.R., and Burns, I.M., 1999, U—Pb geochronology of regional migmatites, East Sutherland, Scotland: evidence for crustal melting during the Caledonian orogeny: Journal of the Geological Society, London, v. 156, p. 1143-1152, doi: 10.1144/gsjgs.156.6.1143.

Kinny, P.D., Strachan, R.A., Rogers, G.R., Friend, C.R.L. and Kocks, H., 2003, U—Pb geochronology of deformed meta-granites in central Sutherland, Scotland: evidence for widespread Silurian metamorphism and ductile deformation of the Moine Supergroup during the Caledonian orogeny: Journal of the Geological Society, London, v. 160, p. 259-269, doi: 10.1144/0016-764901-087.

Leggett, J. K., McKerrow, W. S., and Eales, M. H., 1979, The Southern Uplands of Scotland; a Lower Paleozoic accretionary prism: Journal of the Geological Society, London, v. 136, p. 755-770, doi: 10.1144/gsjgs.136.6.0755.

Moorhouse, V.E., and Moorhouse, S.J., 1983, The geology and geochemistry of the Strathy Complex of north-east Sutherland, Scotland: Mineralogical Magazine, v. 47, p. 123-137.

Péron-Pinvidic, G., and Manatschal, G., 2010, From microcontinents to extensional allochthons: witnesses of how continents rift and break apart?: Petroleum Geoscience, v. 16, p. 189-197, doi: 10.1144/1354-079309-903.

Schmidt, M.W., and Jagoutz, O., 2017, The global systematics of primitive arc melts: Geochemistry, Geophysics, Geosystems, v. 18, p. 2817-2854, doi: 10.1002/2016GC006699.

Stone, P., 2014, The Southern Uplands Terrane in Scotland – a notional controversy revisited: Scottish Journal of Geology, v. 50, p. 97-13, doi: 10.1144/sjg2014-001.

Strachan, R.A., Holdsworth, R.E., Krabbendam, M., and Alsop, G.I., 2010, The Moine Supergroup of NW Scotland: insights into the analysis of polyorogenic supracrustal sequences, *in* Law, R.D., et al., eds., Continental Tectonics and Mountain Building – The Legacy of Peach and Horne: Geological Society, London, Special Publication 335, p. 233-254, doi: 10.1144/SP335.11.

Vink, G.E., Morgan, W.J., and Zhao, W.L., 1984, Preferential rifting of continents: a source of displaced terranes: Journal of Geophysical Research, v. 89, p. 10072-10076, doi: 10.1029/JB089iB12p10072.

Waldron, J. W.F., and van Staal, C.R., 2001, Taconian orogeny and the accretion of the Dashwoods block: A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, p. 811-814, doi: 10.1130/0091-7613(2001)029<0811:TOATO>2.0.CO;2.

Waldron, J.W.F., Schofield, D.I., Murphy, J.B., and Thomas, C.W., 2014, How was the Iapetus Ocean infected with subduction?: Geology, v. 42, p. 1095-1098, doi: 10.1130/G36144.1.

Figure captions

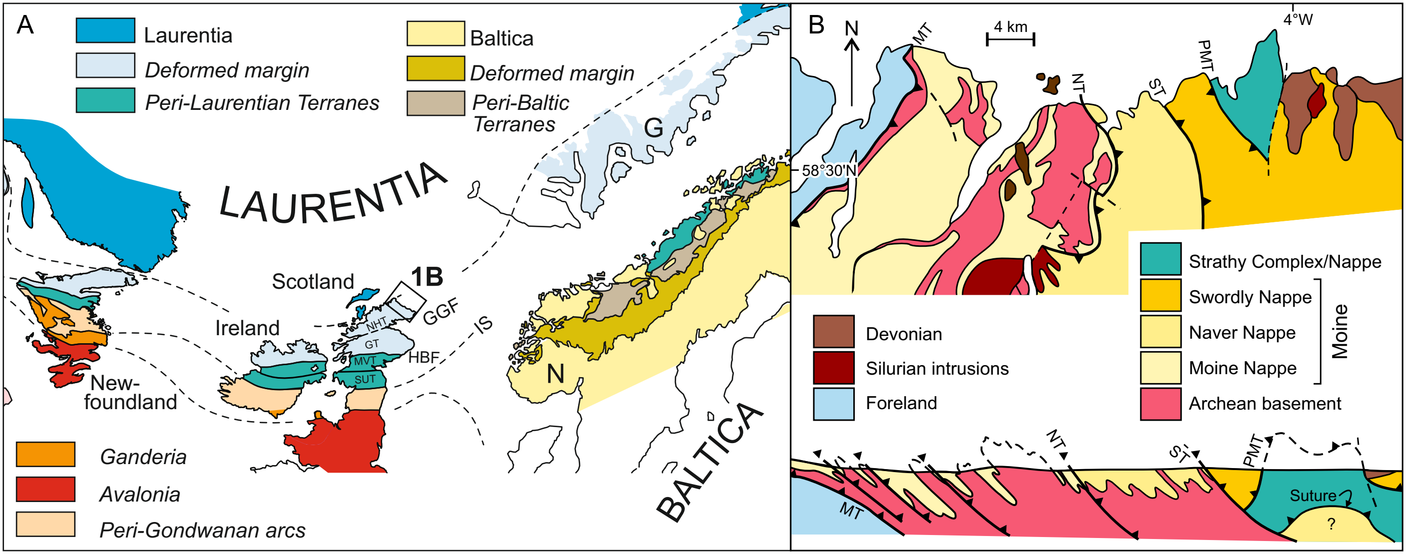
Figure 1. A: Simplified map of the Appalachian-Caledonide orogen, modified from Waldron et al., (2014). GGF, Great Glen Fault; HBF, Highland Boundary Fault; NHT, Northern Highlands Terrane; GT, Grampian Terrane; MVT, Midland Valley Terrane; SUT, Southern Upland Terrane. B: Geological map of the Caledonides of northern Scotland (see 1A for location, modified from Burns et al., 2004) with interpretative cross-section. MT, Moine Thrust; NT, Naver Thrust; ST, Swordly Thrust; PMT, Port Mor Thrust.

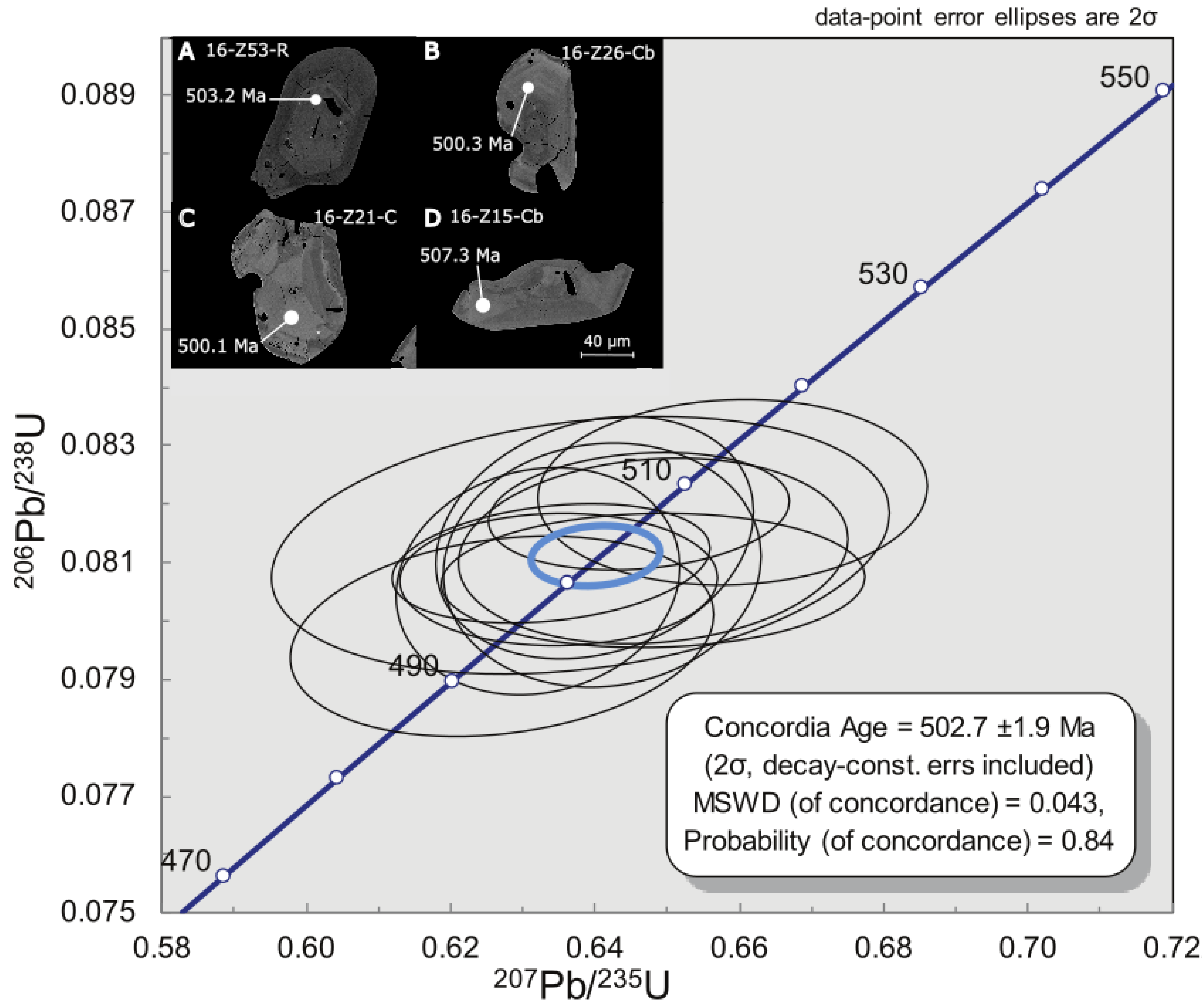
Figure 2. U-Pb Concordia diagram for zircon analyses from sample RS-14-16 (Strathy Complex grey gneiss), together with CL images of representative zircon grains. Laser pits are shown as circles together with site number and the indicated $^{206}Pb/^{238}U$ age.

Figure 3. Pressure-temperature diagram showing: a) P-T paths and peak metamorphic conditions for the Naver Nappe ① (Friend et al., 2000), the Strathy Complex ② (see text and Supplementary Publication for details), and the Swordly Nappe ③ (Kinny et al., 1999), b) our inferred tectonic settings for these different metamorphic environments either prior to or during the Grampian

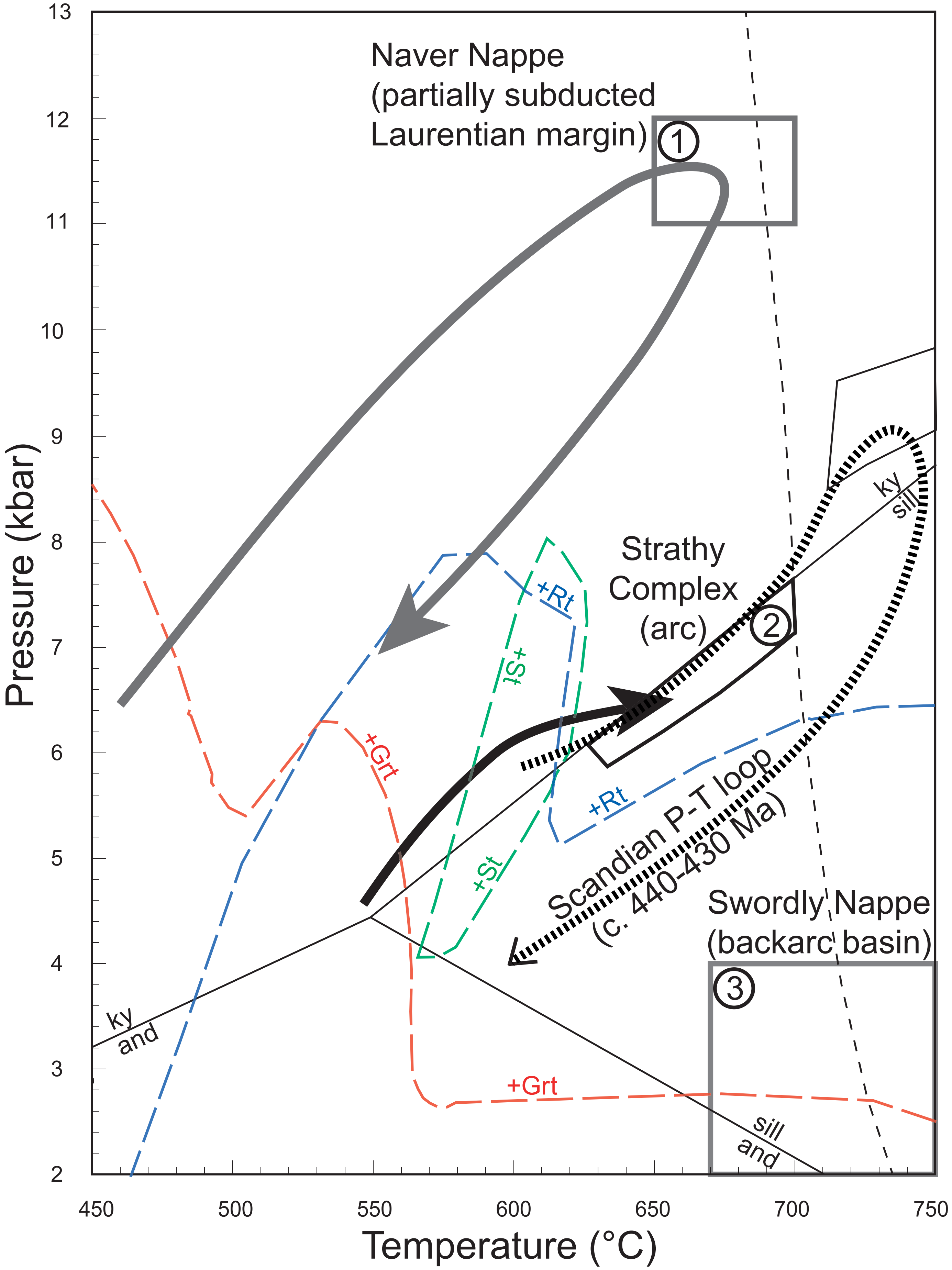
(Ordovician) orogeny (see text for discussion), and c) the P-T path for the Naver Nappe during the Scandian (Silurian) orogeny (Ashley et al., 2015).

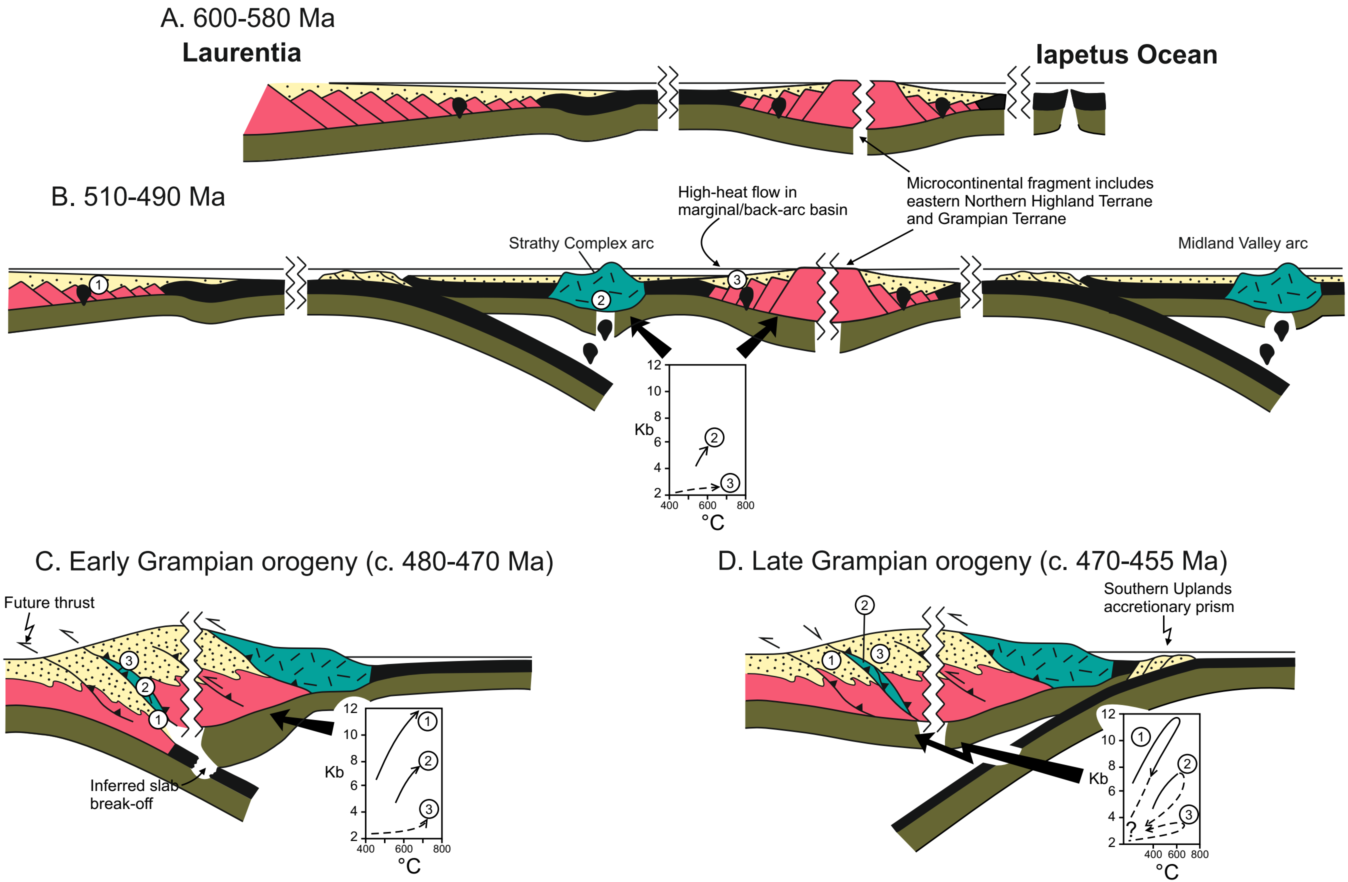
Figure 4. Plate tectonic model for the late Neoproterozoic to Ordovician evolution of the Scottish Laurentian margin and the Strathy Complex together with simplified PT diagrams (see text for discussion). 4B shows the tectonic settings of the Moine rocks of the future Naver Nappe ①, the Strathy Complex arc ② and the Swordly Nappe migmatites ③. 4C shows their relative positions following arc-continent collisions and thrusting, and then in 4D their juxtaposition at approximately the same crustal level following tectonic and erosional thinning.


A
Laurentia
Deformed margin
Peri-Laurentian Terranes
Baltica
Deformed margin
Peri-Baltic Terranes
LAURENTIA
G
Scotland
1B
GGF
NHT
GT
MVT
SUT
HBF
IS
Ireland
New-foundland
N
BALTICA
Ganderia
Avalonia
Peri-Gondwanan arcs
B
N
MT
4 km
4°W
PMT
NT
ST
58°30'N
Strathy Complex/Nappe
Swordly Nappe
Naver Nappe
Moine Nappe
Archean basement
Moine
Devonian
Silurian intrusions
Foreland
MT
NT
ST
PMT
Suture
?



data-point error ellipses are 2σ
A 16-Z53-R
503.2 Ma
B 16-Z26-Cb
500.3 Ma
C 16-Z21-C
500.1 Ma
D 16-Z15-Cb
507.3 Ma
40 µm
550
530
510
490
470
0.089
0.087
0.085
0.083
0.081
0.079
0.077
0.075
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
206Pb/238U
207Pb/235U
Concordia Age = 502.7 ±1.9 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 0.043,
Probability (of concordance) = 0.84


Naver Nappe
(partially subducted
Laurentian margin)
1
Strathy
Complex
(arc)
2
Swordly Nappe
(backarc basin)
3
Scandian P-T loop
(c. 440-430 Ma)
+Rt
+St
+Grt
ky
sill
and
Pressure (kbar)
Temperature (°C)
13
12
11
10
9
8
7
6
5
4
3
2
450
500
550
600
650
700
750



A. 600-580 Ma
Laurentia
Iapetus Ocean
B. 510-490 Ma
Microcontinental fragment includes eastern Northern Highland Terrane and Grampian Terrane
High-heat flow in marginal/back-arc basin
Strathy Complex arc
Midland Valley arc
Kb
°C
C. Early Grampian orogeny (c. 480-470 Ma)
Future thrust
Inferred slab break-off
D. Late Grampian orogeny (c. 470-455 Ma)
Southern Uplands accretionary prism