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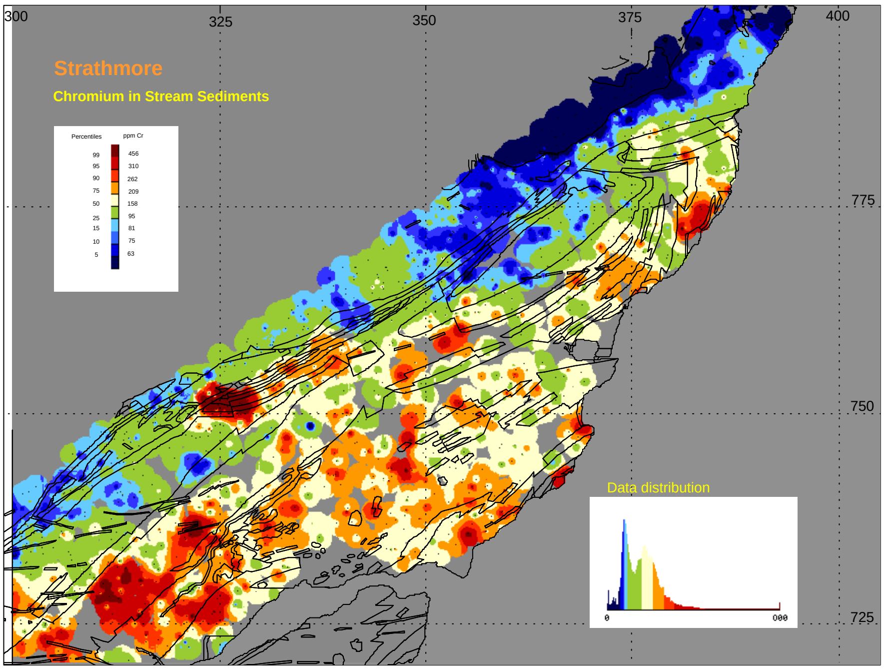
Preliminary Report on the Regional Geochemistry of Strathmore

(including comparisons with Ayrshire)

Economic Minerals and Geochemical Baselines programme

Integrated Geoscience Surveys (Northern Britain) programme

Internal Report IR/04/113



Dr Neil Breward

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/04/113

Preliminary Report on the Regional Geochemistry of Strathmore

Dr Neil Breward

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Foreword

This report is intended as a discussion document for contributors to the Midland Valley of Scotland Integrated Surveys multidisciplinary team working on the new geological mapping phase of the Strathmore area of Scotland. It contains geochemical maps derived from G-BASE stream sediment data, and a brief base-level provisional interpretation of these with regards to the provisional 1:250k geological linework provided. Notes from a project meeting are included in the 'Discussion' section. In terms of 'Cryptogeology' studies it is anticipated that synergistic feedback between the geochemistry and observations by the field geologists and others will strengthen the interpretation of both.

Acknowledgements

Thanks to Phil Stone, Maxine Akhurst and the Strathmore mapping project team for stimulating and valuable discussions on the geochemistry and geology of the area. Special thanks to Maxine Akhurst for the notes of the July 1st meeting which form the basis of the 'Discussion' section.

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Summary

The G-BASE stream sediment geochemistry data and the derived maps are being used as a valuable tool for the examination of the 'cryptogeology' of the Strathmore area, as an aid to the new re-mapping project. Various broad patterns, significant trends and local anomalies have been observed, discussed, and fed into the knowledge-base of the project making an important contribution to understanding the geology of the area.

1 Introduction

A suite of regional geochemical maps were prepared covering the Strathmore district of the Midland Valley of Scotland, using existing G-BASE stream sediment data from samples collected in 1979-1980 and originally published in the East Grampians geochemical Atlas (BGS, 1991).

The area chosen has the following corner points: (OS National Grid).

Minimum Easting	300 000 m
Maximum Easting	400 000 m
Minimum Northing	720 000 m
Maximum Northing	800 000 m

This area was chosen to cover all of the areas included in the Strathmore remapping project of the Midland Valley Integrated Survey, and include areas of Dalradian metasediments and associated igneous intrusions to the north of the Highland Boundary Fault for geochemical comparison with the predominantly Siluro-Devonian tract of Strathmore itself, and to trace possible provenance or glacial transport pathways. However, data for the area of Fife, south of the firth of Tay, is not included in this study.

The maps were produced using the inverse-distance weighting gridding facility written in BGS as an add-on module to NIH-Image™ along with histograms and plot details files (Breward and Herd, 1998). The raster files produced were incorporated into GIS, along with the existing solid 250k geological linework, keys and blanking polygons, initially in MapInfo workspaces and printed out at A3 at an approximate scale of 1cm to 3 km. The raster files and data were later made available to the project GIS.

2 Element descriptions

Some twenty-three elements were used for the initial pilot study, excluding some (such as lead and zinc) which were expected to have more of an anthropogenic than geogenic signature. Several three-element combinations and ratio images were also created in order to examine more complex signatures. Brief notes on these are explained below. These are provisional and are subject to ongoing revision as more information comes to light.

2.1 BORON

Much of the siluro-Devonian tract of Strathmore is marked by low to moderate B values with very low values over the igneous rocks west of Dundee. High levels are present over the Dalradian Southern Highlands Group (SHG) to the north of the Highland Boundary Fault and these extend over the adjacent Devonian outcrop especially in the Howe of the Mearns area, along the North Esk valley, and extending to Laurencekirk and Stonehaven. Very low values associated with the Mountbattock granite also extend eastwards over the SHG to the coast north of Stonehaven suggesting a generally north-easterly movement of glacial debris in both areas. Local anomalously high B values may be associated with areas of quaternary clays.

2.2 BARIUM

The most notable feature is a large patch of moderate to high Ba values extending from the HBF north of Kirriemuir and bounded by NW-SE lines through Montrose and Dundee, giving a superficially Delta-like pattern. This crosses the dominant structural and lithological boundaries and although much of the area is occupied by sandstones and shales of the Arbuthnott Group and partly corresponds with this outcrop, there is no definite link to this formation and this suggests a quaternary influence rather than a primary lithological or mineralisation signature. However, checks should be made for any reports of barite mineralisation or cementation of these sandstones. Alternatively, the Arbuthnott Group sandstones may have a significant SHG component – probably worth checking the sandstones for derived minerals.

2.3 CALCIUM

With the SHG Dalradian and Mountbattock granites being marked by very low CaO values there is again some evidence of spread – whether glacial or Recent - over the adjacent Devonian in the Howe of the Mearns area. The most significant area of high CaO values extends from the Forest of Alyth to the Tay between Perth and Dundee, and is more closely associated with the intermediate and basic lavas and intrusions than the sedimentary terrane, although some high values over the sandstones and conglomerates of the Garvock Group near Coupar Angus possibly indicate derived or interbedded basic or intermediate igneous material.

2.4 CHROMIUM

The Devonian rocks of Strathmore are notable for their regionally-high Cr values which contrast strongly with very low values over the Dalradian metasediments and granitic terrane north of the HBF. Curiously, but probably due to limited outcrop and poor exposure, the Highland Boundary Series which has some ophiolitic character, is not well shown by this image. However, very high values (up to 1963 ppm Cr) occur in a group of eight sites over sandstones and conglomerates at [^{3}26, ^{7}51] near Alyth. These values strongly imply an *ultrabasic* component, especially as high levels of Ni and MgO are also present here. However, high levels of tin (up to 80 ppm Sn) at the same sites also imply a granite-derived heavy mineral suite. Low levels of Cu, Pb and Zn rule out ‘normal’ anthropogenic contamination here. Relatively low Cr values predominate over the sandstones of the Strathmore Group, but the sandstones and conglomerates of the Garvock Group are marked by a broad area of very high Cr levels, especially north of Perth, where values up to 800 ppm Cr are present. Moderate to high levels are also present over the volcanics NE of Perth and the sandstones of the Stratheden Group to the SE. Moderate Cr levels (but still high by national standards) are present over the Arbuthnott Group sandstone/shale outcrop and also near Inverbervie. The major break in Cr levels appears to occur between the Strathmore and Garvock groups, and is sufficiently strong to imply a major change in provenance.

2.5 COBALT

Cobalt shows high levels over the SHG Dalradian and the south of the Mountbattock granite, but here there is strong correspondence with the Manganese distribution, implying that much of this pattern of elevated Co values is due to secondary Mn-oxide sorption. Elsewhere, much of the sedimentary tract is low in Co, with values typically < 14 ppm. Higher levels are present over the volcanics NE of Perth.

2.6 COPPER

There is a marked urban-industrial 'halo' of anthropogenic copper around Dundee, but elsewhere the Cu distribution is rather patchy with few distinct features. Levels over the volcanics are generally higher than over the sedimentary tract, as might be expected, although rather isolated areas of higher Cu values occur (with up to 200 ppm Cu, but mostly around 100 ppm) over parts of the Strathmore and Garvock groups. Only over the Arbuthnott Group east of Arbroath is there a consistent steady Cu background of 35-45 ppm.

2.7 GALLIUM

Gallium is usually associated with aluminous minerals and is therefore usually an effective indicator of high levels of clay minerals and feldspars especially in argillaceous rocks and also in granites and impure sandstones with a strong felspathic or clay component. High levels are present over the SHG Dalradian metasediments and the Mountbattock granite, but much of the sedimentary tract is marked by low to moderate Ga values. The interesting exception is the Arbuthnott Group sandstone outcrop and its associated volcanics in the core of the Sidlaw anticline between Dundee and Montrose. This shows a broad area of moderately high values, typically 14-20 ppm Ga, though it is not yet clear quite what this represents. The core of the anticline naturally exposes older strata which may have more Dalradian source material than the later sediments.

2.8 IRON

The distribution of iron actually shows some similarities with that of gallium, with high levels over the SHG Dalradian metasediments and the (south-western part of) the Mountbattock granite, and a prominent broad enrichment over the Arbuthnott Group sediments and volcanics between Dundee and Montrose. Elsewhere, locally high levels are present over the volcanics in the Sidlaw Hills NW of Perth. Very low levels are also present over parts of the sedimentary sequence, especially over the sandstone and conglomerate units.

2.9 LANTHANUM

Lanthanum shows a strong association of high La values with the Mountbattock granite, and this extends to the NE over the SHG metasediments north of Stonehaven and also over the Devonian sediments extending south towards Montrose. Very low La values mark the area northwest of Alyth and Blairgowrie, but elsewhere the La distribution is patchy and shows no distinct trends.

2.10 MAGNESIUM

The Magnesium distribution is dominated by very low levels over the granite and SHG Dalradian tracts, and high levels over the more basic volcanics. However, Mg also shows high levels, corresponding with high Cr and Ni values, at the multi-site anomaly near Alyth (see Cr description). Elsewhere the area between Dundee and Montrose shows broadly elevated levels and the Garvock Group sandstones southwest of Arbroath show high Mg values. This suggests that these areas have more volcanic horizons, minor intrusions and volcanoclastic sediments than are shown at the 250k scale linework.

2.11 MANGANESE

With high values over the SHG Dalradian and granites, and only a rather patchy and indistinct pattern elsewhere, Mn seems to be more controlled by secondary oxide precipitation than by either bedrock or Quaternary lithology. The close link of the Mn distribution pattern with that of Co also supports this interpretation.

2.12 NICKEL

The multi-site anomaly near Alyth is the most prominent area of very high Ni values, with several sites > 100 ppm up to a maximum of 327 ppm here, associated with very high Cr and Mg values (but, curiously, very low V levels which also suggests an ultrabasic rather than basic igneous source). Nickel levels are also high over the basic volcanics and intrusions of the Sidlaw Hills and also over parts of the Arbuthnott Group sedimentary tract between Dundee and Montrose, suggesting a basic igneous source either from interbedded lavas or volcanigenic sediments.

2.13 POTASSIUM

The potassium (K_2O) distribution is dominated by high levels over the SHG Dalradian and the Mountbattock granite, and notably very low levels over the area around Alyth and Blairgowrie (cf La) and the volcanics of the Sidlaw Hills outcrop. Northeast of Dundee a patch of moderately high K_2O values is part of a complementary pattern to that of Ga, suggesting that the south-western half of the Arbuthnott Group sandstone and shale outcrop is more felspathic and less clay-rich than the north-eastern part. South-west of Stonehaven, a more diffuse pattern of high K_2O values suggests the spread of glacial or recent superficial deposits derived from the nearby SHG and granites.

2.14 RUBIDIUM (and Rb/K_2O)

The distribution pattern of Rb is very similar to that of K_2O except that it lacks the enrichment over the Arbuthnott Group outcrop northeast of Dundee. The reason for this differentiation is not yet clear. The Rb/K_2O map reveals a strong Rb enrichment over the SHG and granites, and superficial deposits derived from these, and confirms the relatively low Rb over the south-western part of the Arbuthnott Group outcrop compared to the north-west part.

2.15 STRONTIUM

Strontium levels are mostly low over the SHG Dalradian and the Mountbattock granite, and superficial deposits derived from them. Higher levels are present in the Alyth-Blairgowrie area, though these are not spatially coincident with the very high Cr-Ni anomaly in this area and are more closely linked with the volcanic rocks rather than the sandstones and conglomerates. Elsewhere high Sr levels are also associated with the volcanic outcrops, especially in the Sidlaw Hills.

2.16 TITANIUM

The TiO_2 distribution is strongly influenced by the volcanic outcrops of the Arbuthnott Group in the Sidlaw Hills and elsewhere, and high levels are also present over conglomerates of the Arbuthnott Group northeast of Alyth and also over parts of the overlying Garvock Group, suggesting that much volcanigenic material is present in these sedimentary formations at this level. There is however no correlation with the very high Cr-Ni anomaly near Alyth. Very low TiO_2 levels mark the Mountbattock granite outcrop and the SHG Dalradian north of Stonehaven, the latter may be due to the spread of Ti-poor superficial deposits derived from the granite. Elsewhere, some high TiO_2 values may reflect the presence of basaltic dykes, for example between Perth and Dunkeld, but otherwise the distribution pattern is somewhat indistinct.

2.17 URANIUM

The high levels present over the Mountbattock granite extend to the northeast over the SHG north of Stonehaven, but there is a very sharp geochemical gradient about 2km from the boundary to the SE of the granite. Elsewhere the younger formations such as the Strathmore Group sandstones are enriched in U relative to the older divisions, although moderately high levels are present over the Arbuthnott Group in the tract between Dundee and Montrose. The main volcanic outcrops and the Stratheden outcrop of Tayside are all low in U, although the outcrop of the latter is poorly exposed and covered by alluvium..

2.18 VANADIUM

Vanadium is most commonly strongly associated with basic igneous rocks, and in the Strathmore area, levels are high over the volcanic rocks and the associated sediments of the Arbuthnott Group and the overlying Garvock Group sandstones and conglomerates which may contain volcanigenic derived material. Levels are particularly high over the Sidlaw Hills between Perth and Dundee, with up to 250 ppm present. However, there is no spatial correlation with the very high Cr-Ni anomaly near Alyth, indeed V levels are rather low here, which suggests an ultrabasic source rather than basaltic debris for this anomaly, or (less likely) that little V is being released from coarse resistate minerals into the sub-150µm material sampled.

2.19 YTTRIUM

Yttrium is high over the Mountbattock granite and the SHG Dalradian to the NE, north of Stonehaven which suggests glacial or Recent superficial granite-derived cover, and thus shows a similar pattern to that given by U and La. The Y pattern is also similar to that of U in that levels are relatively higher over the younger divisions of the Lower Devonian, notably the Garvock and Strathmore Group sandstones and conglomerates. Yttrium levels are very low over the volcanics of the Sidlaw Hills but the patterns are not so clear in other areas.

2.20 ZIRCONIUM

Despite a rather 'noisy' distribution pattern caused by the tendency of Zr (in zircons) to reflect local physical concentration processes in streams, it is clear that Zr is relatively enriched in the higher divisions of the Lower Devonian, such as the Strathmore Group sandstones, compared to both the volcanics and the older sandstones and conglomerates. Although primary zircons are abundant in some granites, clearly this is not true of the Mountbattock outcrop, unless the zircons here are too large to be picked up in the <150 µm sediment fraction. Perhaps the more mature sediments of the Strathmore Group contain finer-grained zircons? However, the Stratheden sediments, of Upper Devonian age, are also mature and are apparently low in Zr, although much of their outcrop is obscured by alluvium.

2.21 Cr-Ni-MgO COMBINATION MAP

This not only highlights the Alyth anomaly clearly, but also shows up the broader, lower-level Cr-Ni area of enrichment over the south-eastern part of the mainly Arbuthnott Group tract between Dundee and Montrose. Several other elements also show a geochemical gradient along a dividing line running approximately NW-SE through Carnoustie and Forfar and this therefore may represent a significant lineament, possibly an internal basin divide or limit of a particular source river.

3 Comparison of Strathmore with Ayrshire (Swanshaw Sandstone).

The Swanshaw Sandstone of Ayrshire is of a similar Lower Devonian age and lithology to the sandstones and conglomerates of Strathmore, and is also associated with basaltic to andesitic volcanic rocks. The Swanshaw Sandstone is also (now) geographically close to the Ballantrae ophiolitic complex, which may have provided some source material for the sandstones. Examination of the wider-area ‘Midland Valley’ geochemical map suggests that high Cr levels are a feature of both the Swanshaw sandstone and the Garvock Group sandstones of Strathmore, with several hundred ppm Cr common in each case. Statistical comparison of stream sediments over these two sandstone units can be made in the following tables. *(see over)*

The top of the formation, underlying the volcanic formation, has high feldspar elements indicating a cryptic heralding of the extrusive volcanism. A high chromium content is typical of the middle part of the formation indicates an ultramafic source. Serpentinised basic clasts had been noted in thin section and the Ballantrae ophiolite was suggested as a source. A heavy mineral suite of high Zr (zircon), Y (sphene, allanite, apatite, garnet) and Ti (rutile, ilmenite, sphene) is also characteristic of the mid-part of the formation. This suggests a recycled sediment source, supported by the absence of high Ni and Mg values that should occur in association with high Cr if this was being eroded directly from the Ballantrae ophiolite. The plot showed high values for all three elements and so was considered to reflect a resistate heavy mineral suite rather than an ultrabasic signal that would have been interpreted as first cycle erosion of an ophiolite source.

The distribution of Mg was considered to possibly reflect dolomitic cements within sandstones. However, the Mg distribution did not correspond with known occurrences of calcretes or dolostones and so this was discounted.

Igneous intrusions with widely ranging composition occur within the base of the Swanshaw Sandstone Formation. High Cu, Zn and Pb values were considered to reflect an igneous derivation. However, high values of B were noted which may be attributed to detrital tourmalines or clay minerals and a B-Li-Ga three component plot shows further information. The plot showed high values for all three components but with higher values of Ga in the northern (younger) part and higher values of B are typical of the southern (older) part of the formation. It was considered likely that the distribution may reflect a variation in the weathered feldspar component of the Swanshaw sandstones. Petrological data should be reviewed to investigate the variation in feldspar composition through the formation.

Table 1. Swanshaw Sandstone outcrop: stream sediment data statistics.

Swanshaw Sandstone				
Element	Mean	Count	Min.	Max.
As	32.222	27	5.0	130.0
Ba	738	56	324	3090
Bi	1.143	56	0.00	3.0
CaO	1.287	56	0.53	3.6
Co	26.982	56	18	73
Cr	401.768	56	101	2460
Cu	40.839	56	20.0	124.0
Fe_2O_3	8.826	56	5.93	15.73
Ga	17.761	56	12.1	23.5
K_2O	2.057	56	1.21	2.95
La	49.286	56	22	99
MgO	2.134	56	0.72	7.15
Mn	2757	56	530	17400
Mo	0.363	56	0.0	2.9
Ni	71.7	56	37	161
Pb	83.57	56	29.0	281.0
Rb	73.95	56	41.0	123.0
SiO_2	59.02	56	0.0	84.8
Sn	38.0	56	0.0	280.0
Sr	231.2	47	94.00	413.0
TiO_2	1.23	56	0.90	1.92
U	3.2	56	2.1	5.6
V	109	56	79	204
Y	34	56	24	59
Zn	288	56	138	1220
Zr	1285	56	358	4396

Table 2. Garvock Group Sandstone outcrop: stream sediment data statistics.

Garvock Group Sandstones				
Element	Mean	Count	Min.	Max.
As	10.756	86	0.0	60.0
Ba	669.601	138	389	2859
Bi	1.341	138	0.0	9.0
CaO	1.457	138	0.22	4.85
Co	17.667	138	5	43
Cr	307.094	138	69	1115
Cu	29.413	138	11.0	103.0
Fe_2O_3	7.243	138	2.84	14.28
Ga	12.277	138	5.0	20.1
K_2O	2.351	138	1.10	3.87
La	53.355	138	0	189
MgO	2.142	138	0.61	4.47
Mn	1841	138	216	13199
Mo	0.100	138	0.1	0.1
Ni	53.848	138	25	99
Pb	46.957	138	5.0	451.0
Rb	82.413	138	25.0	179.0
SiO_2	67.075	133	7.0	87.4
Sn	9.984	138	0.10	233
Sr	196.6	135	1.25	360
TiO_2	1.435	137	0.81	2.85
U	4.0	138	0.40	11.37
V	99.4	138	41	212
Y	35.0	138	17	165
Zn	145	138	16	553
Zr	1328	138	297	3763

These data show that the Swanshaw sandstone has higher levels of basic elements such as Ni and Co, plus higher levels of Cu, Pb, Sn and Zn which may be in part anthropogenic, while the Garvock Group sandstone is more quartzose and richer in ‘acid’ felspathic elements such as K_2O, La, Rb and Zr. For other elements the differences are small and probably not significant. Chromium levels are very high on the regional scale in both formations, though somewhat higher in the Swanshaw.

The implication is that the Swanshaw sandstone does have a higher basic component input than the Garvock Group, which is richer is ‘acidic’ materials, but both appear to have an ultrabasic component. In the case of the Swanshaw Sandstone it is tempting to regard the Ballantrae ophiolite as an important sediment source, but it appears unlikely that this could be a source for the Garvock Group sandstones. The origin of the high Cr levels in the latter is open to debate, but it is worth noting that stratigraphically equivalent rocks in Wales also have similar high Cr values, and it may be that the contemporary source of the Cr now lies outside the UK landmass.

Ayrshire: Carrrick Volcanic Formation

The GBASE plots were compared with whole rock geochemical analyses of a traverse collected up the sequence of the outcrop of the formation. The whole rock analyses illustrated a contrast in the middle part of the formation characterised by lower Cr (decrease of 150 ppm) but high Zr and V (increase by 150 ppm). Comparison with the GBASE results showed a decrease in the proportion of Zr despite higher analytical values and it was agreed that the variation was too subtle for determination by GBASE methods.

The GBASE results showed high Zn of the western part of the outcrop of the formation. High B and Li content are noted across the formation, the latter may occur within feldspars or in micas. High B is characteristic of the formation but although high Ba is noted in the underlying sandstones only a single high spot is noted at the boundary. There are background levels of Cu.

A possible occurrence of B ‘hot spots’ in an NNW alignment, including the known area of tourmaline alteration at Foreburn, was not supported by any other elements although faults of this orientation are known in the area.

It may be instructive to compare the Carrick Volcanic Formation with the volcanic formations of Strathmore but this has not yet been examined in detail.

4 Discussion

A draft version of this report was circulated for information and feedback. A list of points had subsequently been compiled for consideration by project staff at a meeting held in Murchison House on July 1st 2004. A preliminary report of the petrography of thin sections within sheet 57 was also available. The elements were discussed mostly as presented in the draft report.

Present at meeting: Neil Breward (NB), Richard Smith (RAS), Emrys Phillips (ERP), Mike Browne (MAEB), Phil Stone (PSTO), Maxine Akhurst (MCA).

4.1 BORON

High B levels were noted over the Southern Highlands Group (SHG) west of the Mountbattock Granite (MB Granite), with an apparent glacial ‘smear’ inferred from the very marked lineaments mapped by Nick Golledge from DTM and LandSat imagery. The B is anticipated to occur in mica, chlorite and tourmaline and is concentrated by stream sedimentary processes relative to the host rock. The granite was also noted as having unusually high yttrium content.

4.2 BARIUM

A broad ‘delta’-shaped band of high Ba content cuts across the centre of the Strathmore area at a high angle to strike, see also gallium and iron. The possible cause was discussed that should be considered during resurvey:

1. Quaternary erosion from the high-Ba SHG west of the Mountbattock granite;
2. barytes mineralisation of the Devonian sandstones e.g. Arbroath, Carnoustie;
3. barytes cementation of the Devonian sandstones.

ERP noted that up to 50% of sandstone can be replaced by carbonate minerals in calcrete and the source of the Ba enrichment might be $BaCO_3$ rather than the more usual barite ($BaSO_4$).

4.3 CALCIUM

The distribution of Ca does not follow that of Ba so the carbonate cementation/mineralisation proposed for Ba distribution is not also accompanied by $CaCO_3$, so a $BaCO_3$ source seems less likely. High Ca is associated with lavas in the western Strathmore area (Alyth to Perth). ERP described how secondary replacement of lavas might produce a rock that is technically a limestone (100% Ca carbonate) with 'ghost' poikilotopic texture. High Ca was noted at some points within the Montrose Volcanic Formation. The reason for this could be:

1. widespread hydrothermal circulation and early alteration where lava sequences are thick;
2. localised hydrothermal circulation and early alteration where lava sequences are thin;
3. alteration associated with later period of alteration as seen in Ayrshire;
4. expulsion of basinal fluids, although probably not as likely due to inadequate basinfill.

4.4 CHROMIUM

Very prominent low Cr values for the SHG and MB Granite, but higher values in the Strathmore area, are evidence that the SHG did not provide the major source of sediment during either lower or upper Devonian times. There may have been early Devonian strata north of the Highland Boundary Fault (HBF) during the Devonian, which has since been removed by erosion.

The geochemical character of lower Devonian lava sequences is considered broadly similar but the Cr content is not consistent. High Cr values are typical for lavas and associated sedimentary rocks around Perth but high and low Cr are noted for the Montrose Volcanic Formation.

Ultrabasic composition (high Cr, Ni and Mg)

The Alyth anomaly: - A 'hot spot' of ultrabasic signature (high Cr, Ni and Mg) but also high in Sn. Contamination by re-use of chromite waste from Glasgow was considered but the anomaly includes eight sample sites and so this was considered unlikely. A sliver of Highland Border Complex rocks of ophiolitic origin was considered possible. A 'bend' in the HBF at this point may have introduced basement rocks as a duplex structure by dextral displacement across the HBF. The Cr values are so high (up to 1963 ppm Cr) that whether natural or man-made, any rocks or deposits could be considered as potentially hazardous to human health and should be investigated further. The mineral species would determine whether the Cr is mobile or not.

ERP suggested that the Sn could come from contained granite clasts. Emplacement of granitic rocks is a common association with major faults. Granitic clasts present in the Crawton Group have undergone whole-rock geochemical analyses and been dated as only 5 Ma older than the host sediment by Rogers and Haughton (1980).

Action. Neil will investigate geochemical results of Rogers and Haughton for Sn content, arrange preparation of grain mounts for thin section from the pan concentrates of the stream sediment samples and review the topography and drainage in the area of the anomaly.

Action. Emrys would examine the mineralogy of the grain mount thin sections.

Action. Maxine to ask Paul Williamson to investigate the possibility of a sliver of possibly ultrabasic basement rocks at Alyth as part of the analysis of regional potential field data.

Action. **Maxine** would organise a day field visit (at a date to be decided) to observe rock or deposit types following completion of other actions.

'Resistate' composition (high Cr, lower Ni and Mg)

A resistate composition (high Cr, lower Ni and Mg) was noted as characteristic for parts of the Strathmore strata. A marked contrast was noted between the Strathmore (low values) and Garvock (high values) groups. There is insufficient data from the Dunottar-Crawton Group; no GBASE sample points within the coastal outcrop and only two samples within the Crawton Basin. MAEB noted that the marked change in composition at the base of the Strathmore Group was associated with evidence of a depositional hiatus given by the common presence of calcrete limestone at the top of the Garvock Group. A similar 'resistate' composition is a distinctive characteristic of the Siluro-Devonian Swanshaw Sandstone Formation in Ayrshire and comparison with the Strathmore sequence should be undertaken. NB described a similar geochemical anomaly from Old Red Sandstone (ORS) Facies sequences in Wales, where background Cr values are characteristic of the lowest and upper ORS Facies whereas lower to mid-ORS Facies rocks (Pragian) rocks are distinguished by high Cr and low Ni. NB considered this 'resistate' mineralogy to be a synchronous UK-wide provenance variation that may have been sourced from Ontario, Canada or from Scandinavia (Bluck, 2000).

Using the 'resistate' composition, the age range of the Swanshaw Sandstone Formation, in comparison with the Strathmore sequence, would be narrowed to younger than the Dunottar-Crawton and older than the Strathmore groups, respectively (Browne et al., 2002). The Carrick Hills Volcanic Formation overlies the Swanshaw Formation. ERP sketched out a comparison of the volcanic and sedimentary sequences in the Ayrshire and Stathmore areas. MAEB noted that within the Arbuthnott-Garvock Group the Montrose and Ochil Volcanic formations lie within the lower Arbuthnott strata whereas the overlying Garvock strata are solely sedimentary in origin. Although the composition of the Devonian lavas is considered broadly similar comparison of existing geochemical analyses of volcanic formations would identify any detailed variation and allow comparison of the Strathmore lava formations (published by Thirlwell (1981; 1983)) with the Carrick Hills Volcanic Formation in Ayrshire (Emrys).

Action. Neil to prepare box and whisker plots of the 'resistate' elements from GBASE sample points within the Arbuthnott, Garvock, Strathmore groups and Swanshaw Sandstone Formation to enable characterisation and comparison of the sedimentary units.

Action. Neil and **Emrys** to collate analyses from Strathmore and Ayrshire, respectively, and compare compositions.

4.5 NICKEL

High Ni content is characteristic of volcanic and associated sedimentary rocks from Dundee to Perth indicating volcanigenic strata may be interbedded with the Dundee Flagstone Formation rocks.. Very high Ni values (327 ppm) are noted at Alyth (see Cr), compared to accepted background values of 30-50 ppm. It was noted that whereas Cr is enriched during weathering and sedimentary processes from rock to stream sediment, Ni content is usually depleted.

4.6 MAGNESIUM

High Mg values are associated with the Arbuthnott strata, particularly the volcanic rocks around Dundee, but not the Montrose Volcanic Formation.

4.7 COBALT AND MANGANESE

The distribution of Co and Mn is influenced by reactions within surface waters and so any patterns are not due to geological factors. However, Co values are elevated in the Alyth ‘hotspot’ whereas Mn values here are notably very low indicating the two elements are not associated due to surface water reactions and the Co enrichment here is due to primary factors.

4.8 COPPER

The copper distribution map illustrates the high values associated with industrial contamination around Dundee and probably in the vicinity of Laurencekirk in the centre of the Strathmore syncline. Although there is an expectation that higher Cu values might be associated with volcanic rocks this was not seen and may be due to the intermediate andesitic rather than basaltic composition.

4.9 GALLIUM, IRON AND POTASSIUM

High values for both Ga and Fe occur in a broad band of south-east trend across the Strathmore area from adjacent to the HBF and spanning parts of the Dundee Flagstone and Montrose Volcanic formations. Ga usually occurs in clay minerals and the cause of this distribution pattern is unclear. Ba also has this distribution although K has a reciprocal distribution and within the two formations is high where Ga, Fe and Ba are low. Several faults of south-east trend are mapped across the Strathmore Syncline in this area and fault-controlled mineralisation was considered a possible cause (see Ba). North of the HBF the high K distribution of the MB Granite cannot have been ‘smeared’ by glacial erosion and transport because an area of low values is noted on the southern and eastern margins of the granite.

Action. Maxine to ask Paul Williamson whether any lineaments of south-east trend are evident from potential field data in this area.

4.10 LANTHANUM

Values for Lanthanum content show no distinct pattern associated with the stratigraphical groups. Very low values are noted over the Arbuthnott Group around Blairgowrie in the western part of the Strathmore area. North of the HBF values for La are very high over the MB Granite (possibly within biotite or accessory minerals such as sphene, apatite, monazite and even minor opx and cpx) and the SHG particularly north-east of the granite.

4.11 RUBIDIUM

Rubidium distribution should mirror K closely, but in some areas does not – see Rb/K_2O map. There is no clear pattern within the Strathmore area. Values are very high over the MB Granite with a halo of higher Rb content all around it (seen in the East Grampians geochemical atlas, BGS 1991).

4.12 URANIUM

Higher values of U seem typical for the Strathmore (?and underlying Garvock) Group within the Strathmore area. North of the HBF the MB Granite and surrounding halo has a very high U signature with an abrupt boundary. Debris arising by erosion of granite may be included in the Strathmore (? and Garvock) groups.

4.13 STRONTIUM

Strontium content within the Arbuthnott Group is high over the Ochil Volcanic Formation and associated sediment yet low over the Montrose Volcanic Formation and interbedded sedimentary strata. ERP noted that Sr distribution may reflect the variation in lava composition and contained feldspars. Low Sr values from the olivine basalts of the Montrose Volcanic Formation, as noted in thin section, and high values from the more andesitic Ochil Volcanic Formation. The MB Granite, north of the HBF, is characterized by uniformly very low Sr values whereas the SHG on either side has low values to the west but high values to the east.

4.14 TITANIUM

There is a broad spread of high Ti content for the andesitic Ochil Volcanic Formation lavas within the Arbuthnott Group in the vicinity of Perth. Although there are also some moderately high Ti values within the Montrose Volcanic Formation and associated strata but the relationship is not as close or consistent. High Ti content near Perth may also reflect the presence of quartz dolerite dykes of east-west orientation.

4.15 VANADIUM

There is a broad high in V content associated with the Arbuthnott Group and no distinction between the Montrose and Ochil volcanic formations despite the contrast in their composition. High values for both V and Ti in the Ochil Volcanic Formation may reflect the presence of a phenocryst phase such as magnetite.

4.16 YTTRIUM

Distribution of Y reflects the presence of heavy minerals such as garnet, sphene, monazite, apatite and pyroxenes; in addition to biotite and feldspars. Within the Strathmore area there is a broad but indistinct association between high Y content and Garvock Group sandstone.

4.17 ZIRCONIUM

There is not a notable pattern of Zr distribution within the Strathmore area. There is an association between higher Zr values and the Garvock and Strathmore groups but this may correspond to the finer grain size of the host rocks and the mineral grain size fraction separated for analysis.

ERP mentioned he had previously received an enquiry from a student of Graham Oliver at St Andrews regarding the mineralogy of heavy minerals from the Old Red Sandstone Facies in the vicinity of Crawton and Stonehaven, and that it would be useful to have any results arising from that work.

Action. Maxine to email Graham Oliver to enquire of any work completed and reported, or if any other information was available.

5 Conclusions

Although the resolution of the stream sediment geochemistry is probably not high enough generally to allow mapping on specific geochemical signatures, coupled with the geochemical heterogeneity of many of the mapped formations, nevertheless the regional-scale variations and more localised anomalies are sufficient to provide useful information to the project.

This is particularly true with respect to the identification of the Alyth anomaly, which may lead to a significant revision of the local geology and/or the identification of a potential geochemical hazard. Elsewhere the lateral variation within some of the mapped units can be readily identified by the geochemistry, as can several clear stratigraphic or structural breaks within both the Old Red Sandstone and the Southern Highlands Group.

In other cases there are geochemical features which cannot be readily acribed to obvious geological or even anthropogenic sources, but may yet be explained as re-mapping proceeds.

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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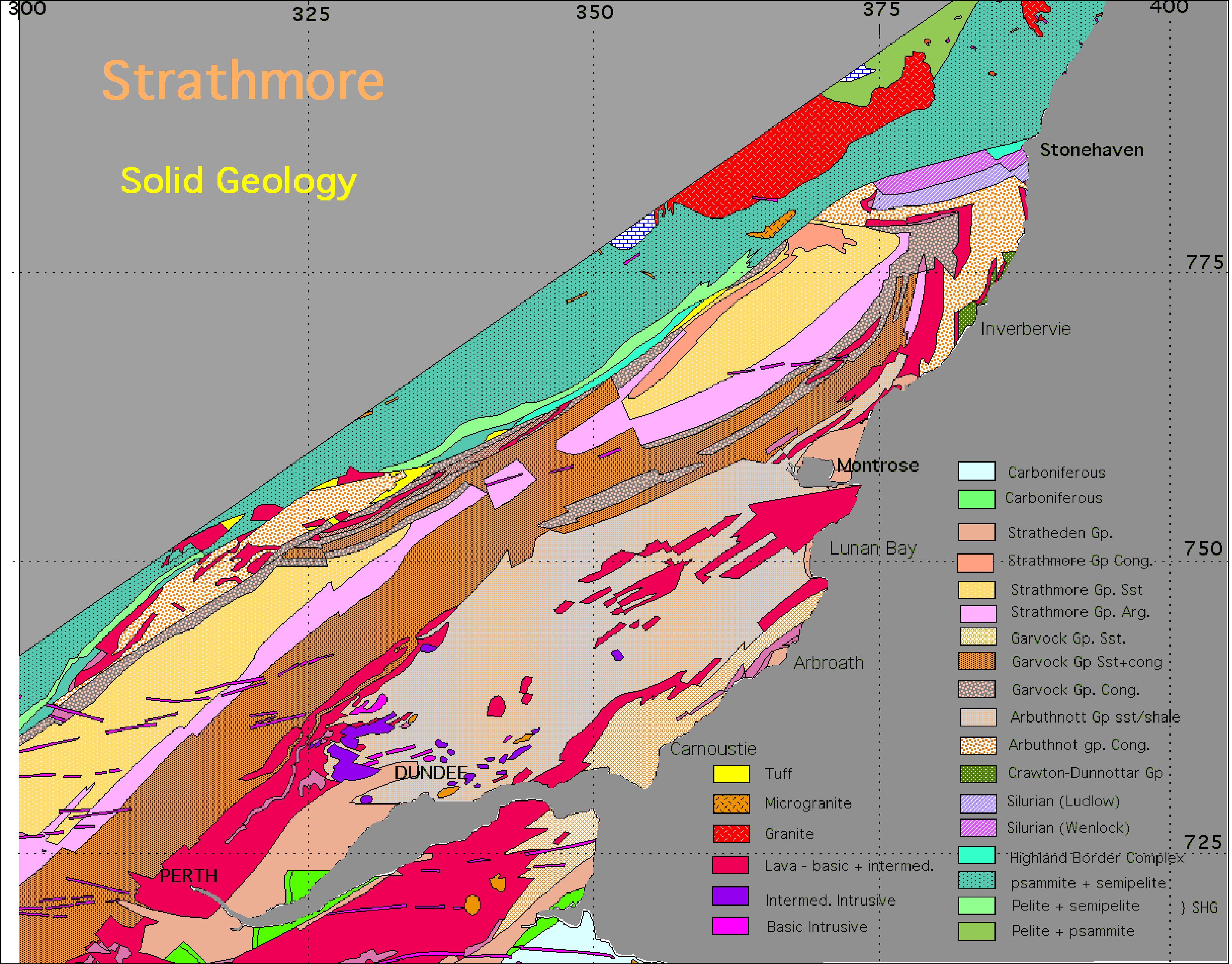
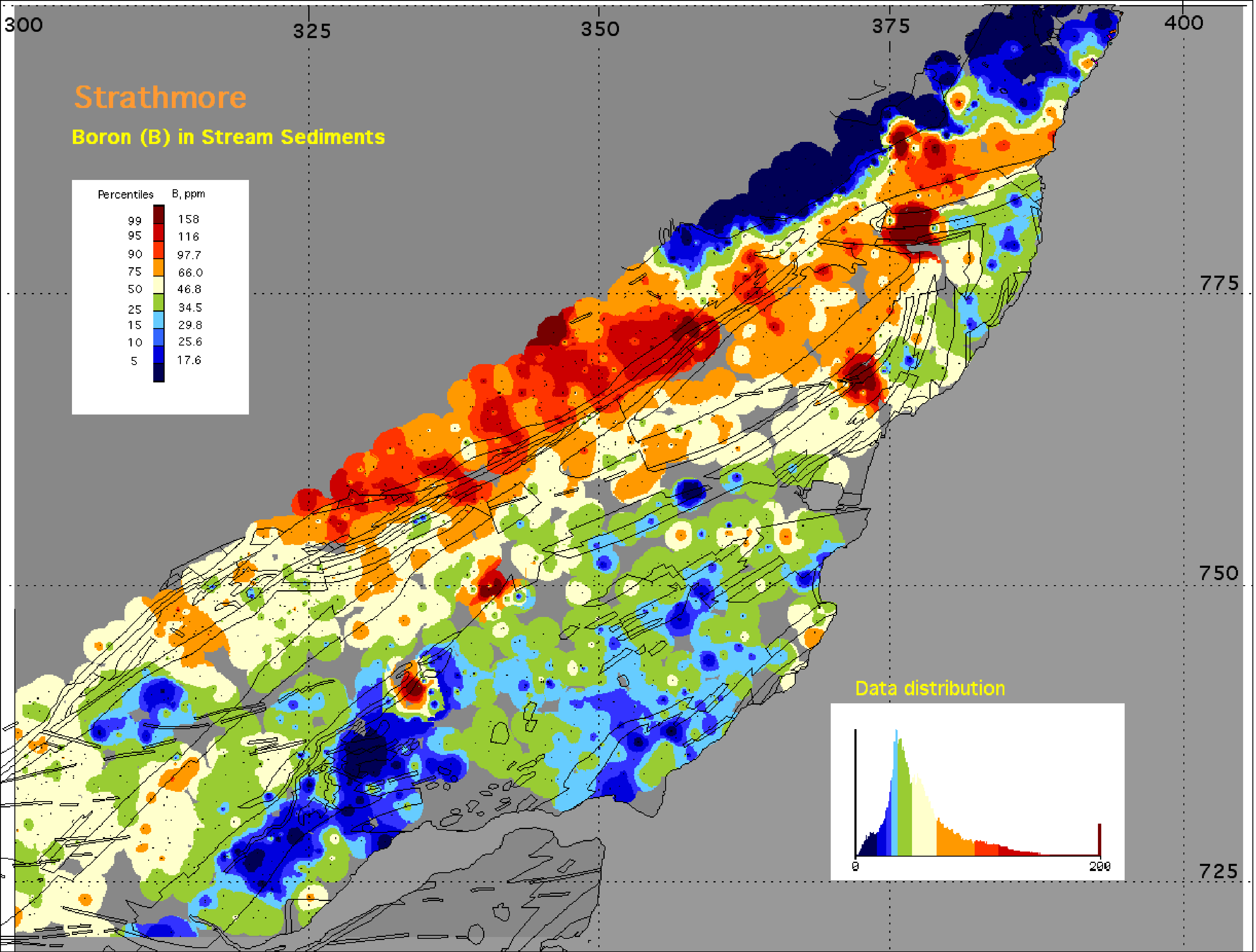
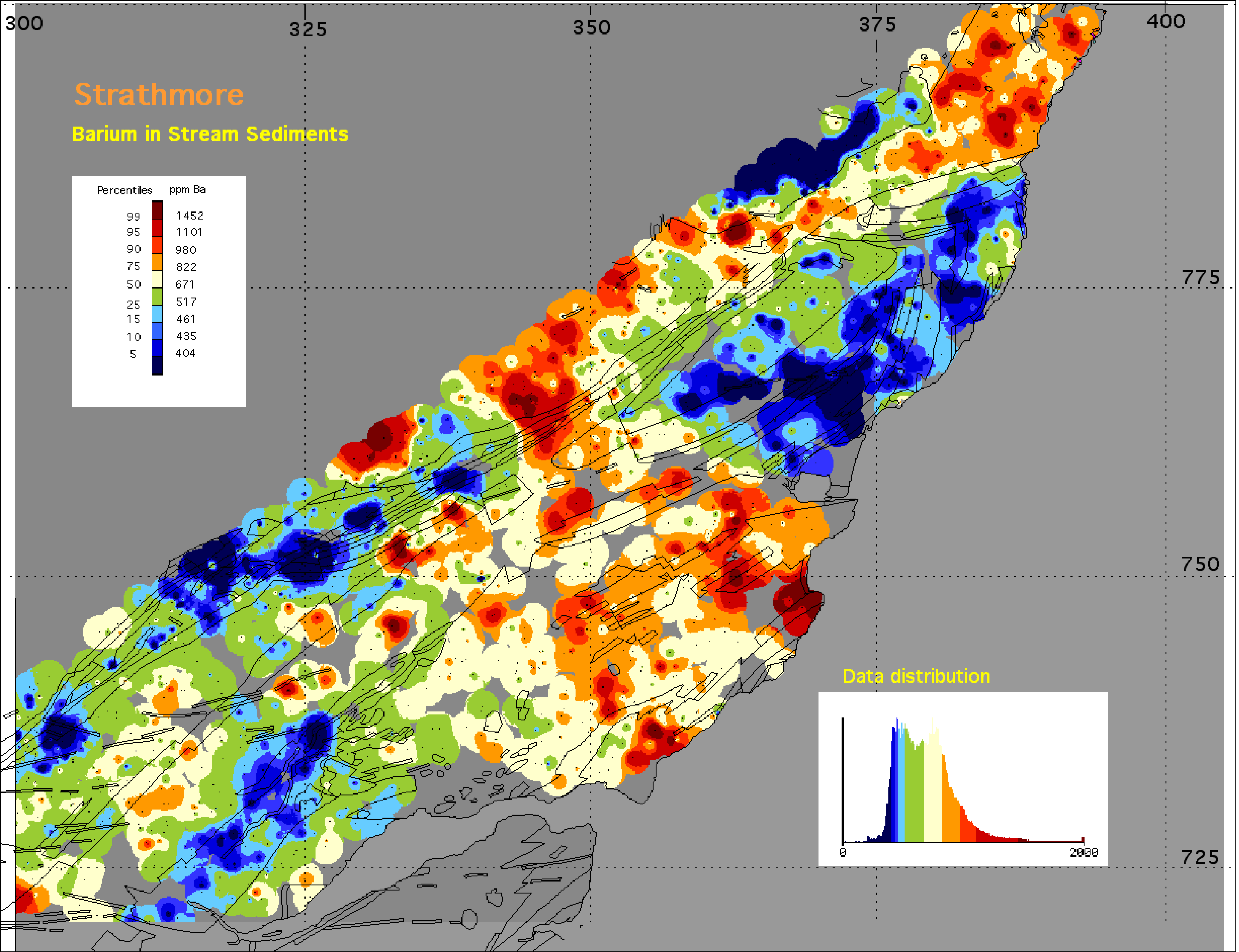
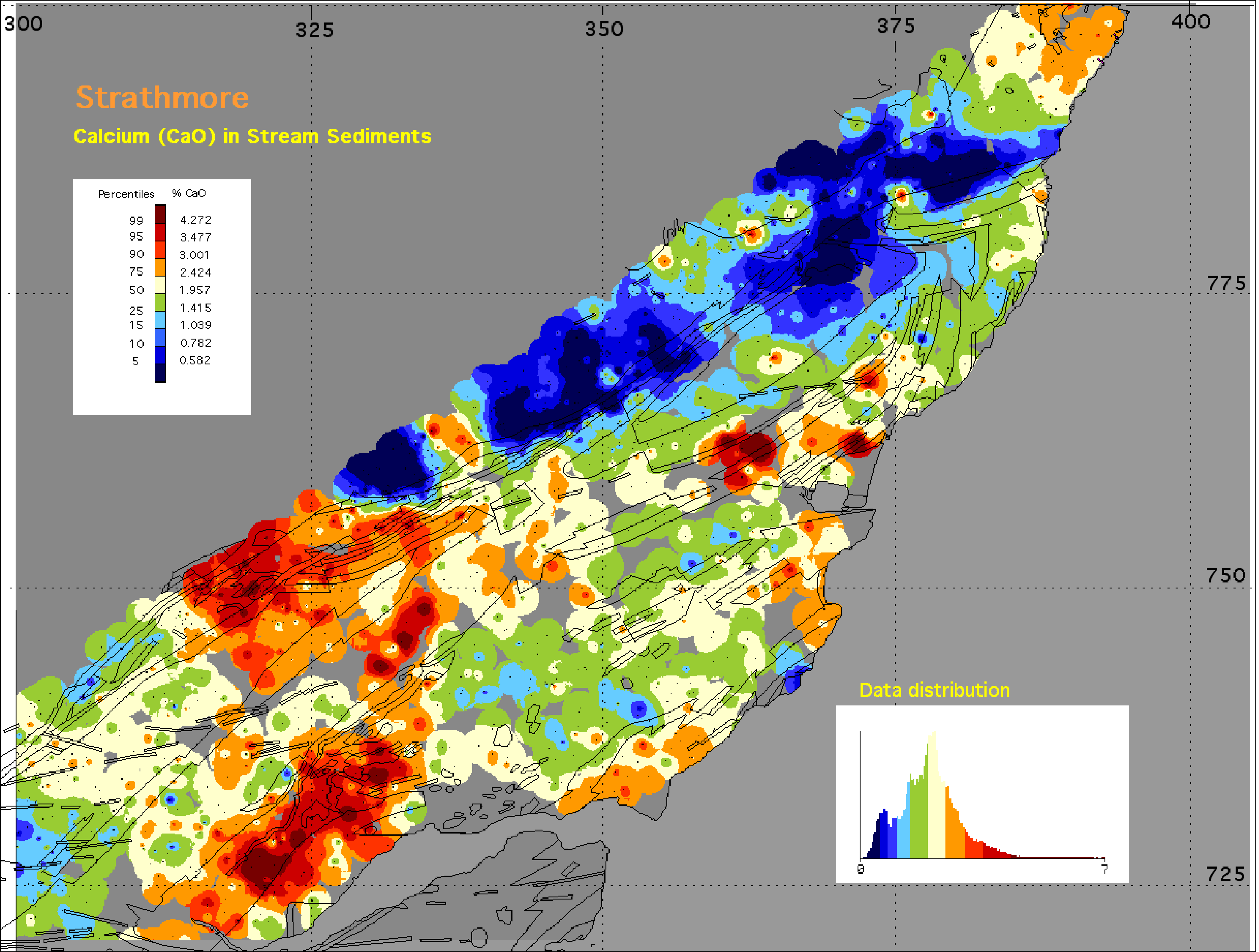


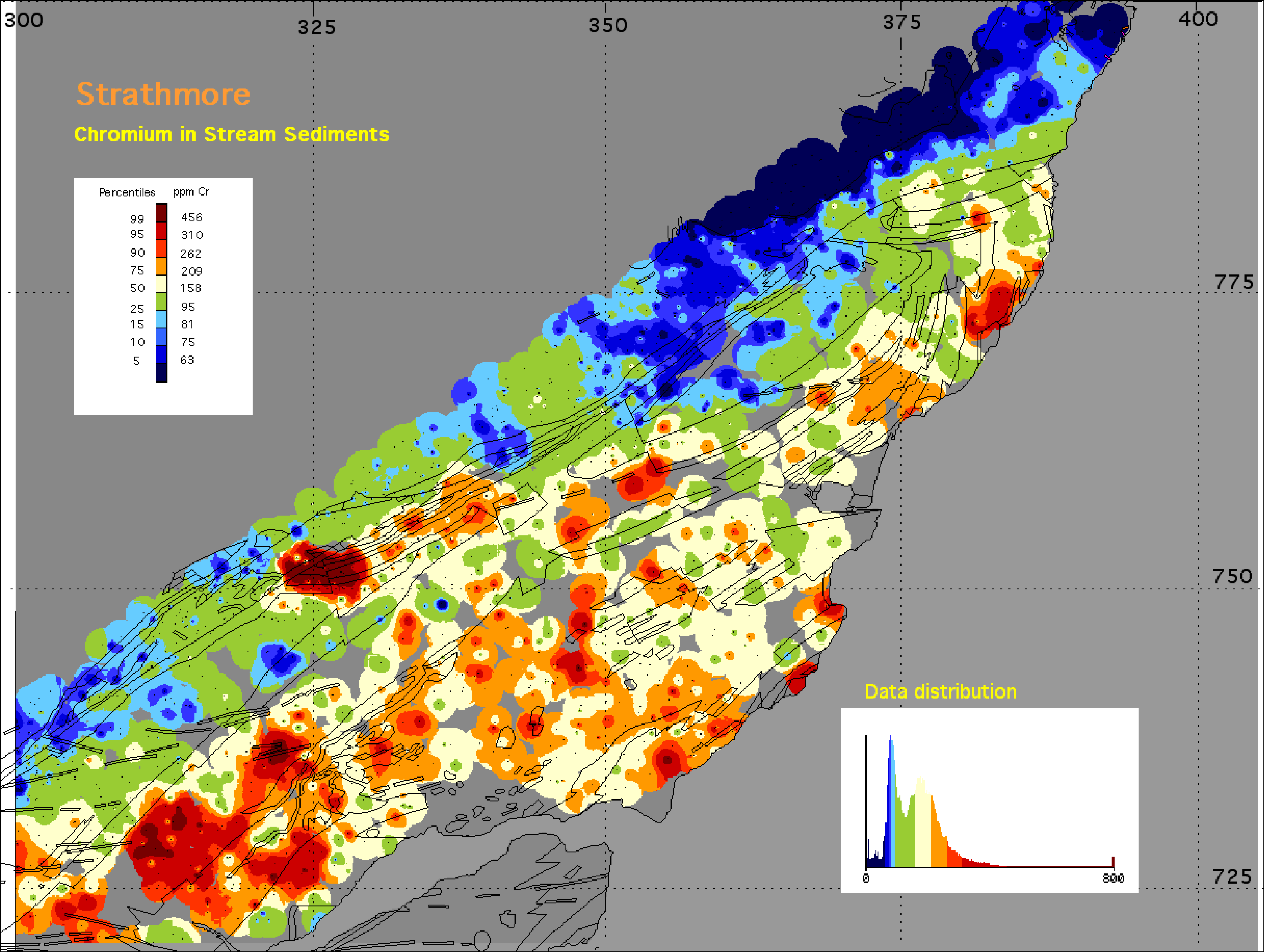
300
325
350
375
400
Strathmore
Solid Geology
Stonehaven
775
Inverbervie
Montrose
Lunan Bay
750
Arbroath
Carnoustie
DUNDEE
PERTH
725
Carboniferous
Carboniferous
Stratheden Gp.
Strathmore Gp Cong.
Strathmore Gp. Sst
Strathmore Gp. Arg.
Garvock Gp. Sst.
Garvock Gp Sst+cong
Garvock Gp. Cong.
Arbuthnott Gp sst/shale
Arbuthnot gp. Cong.
Crawton-Dunnottar Gp
Silurian (Ludlow)
Silurian (Wenlock)
Highland Border Complex
psammite + semipelite
Pelite + semipelite
Pelite + psammite
} SHG
Tuff
Microgranite
Granite
Lava - basic + intermed.
Intermed. Intrusive
Basic Intrusive



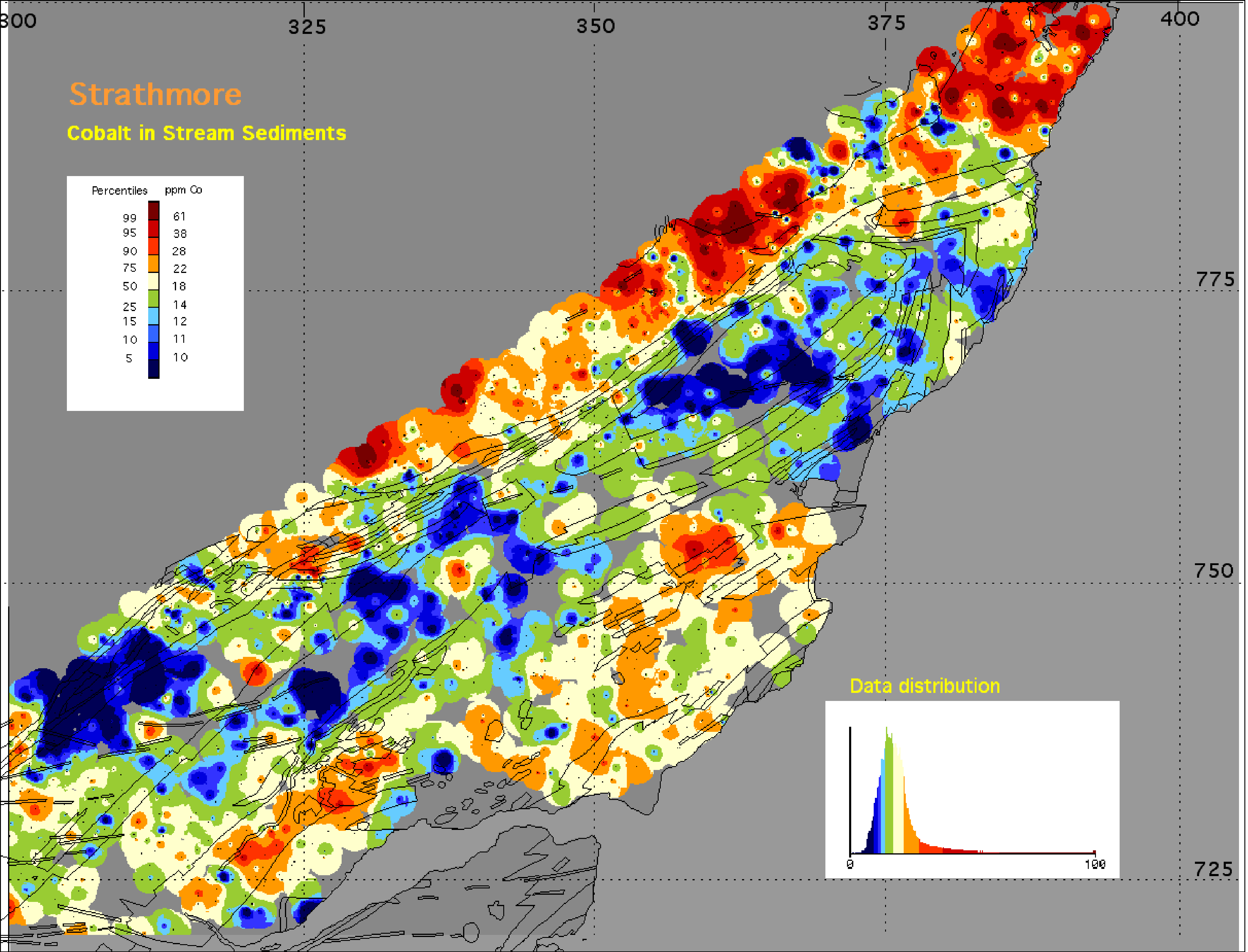
300
325
350
375
400
775
750
725
Strathmore
Boron (B) in Stream Sediments
Percentiles
B, ppm
99 158
95 116
90 97.7
75 66.0
50 46.8
25 34.5
15 29.8
10 25.6
5 17.6
Data distribution
0
200

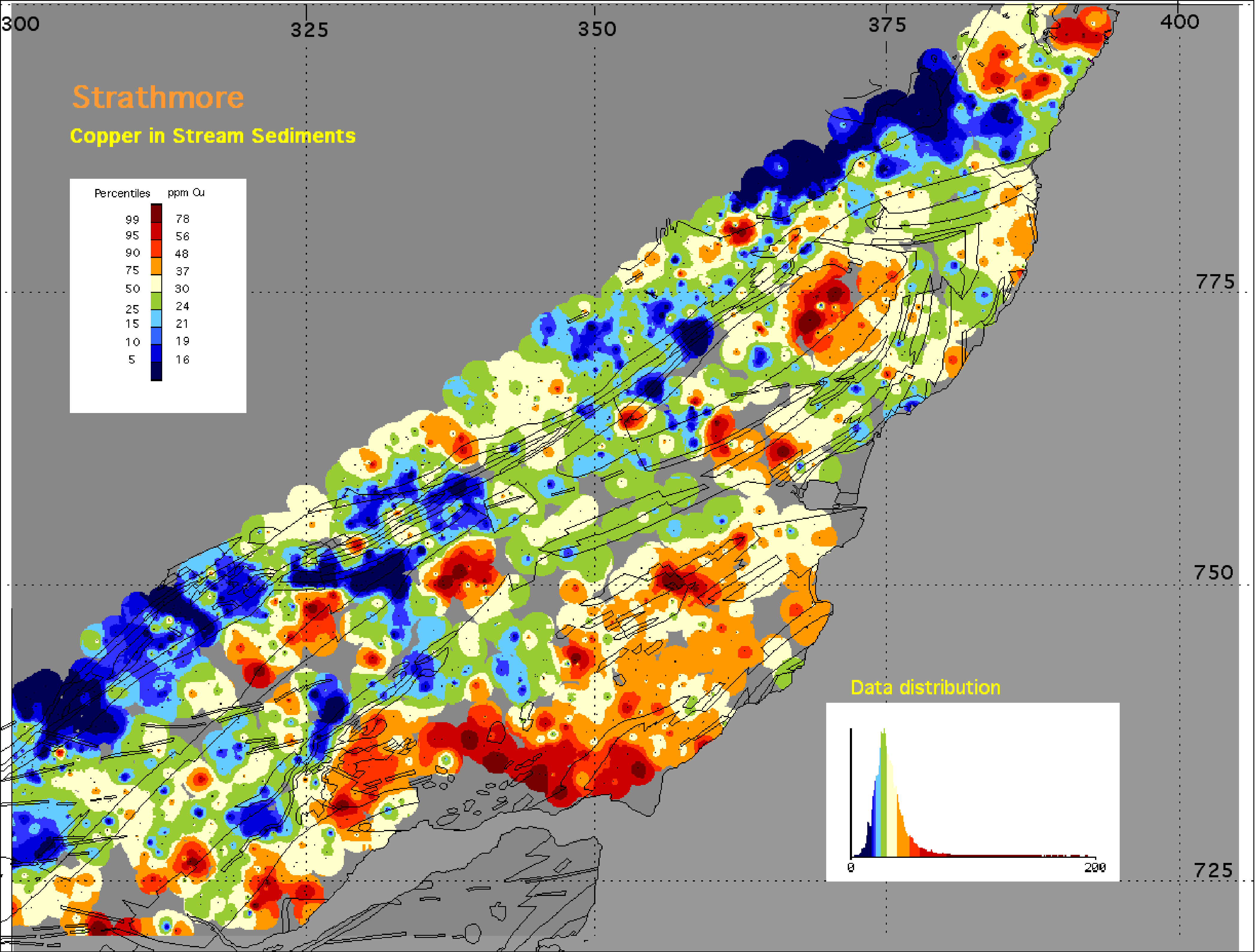

Strathmore
Barium in Stream Sediments
Percentiles
ppm Ba
99
1452
95
1101
90
980
75
822
50
671
25
517
15
461
10
435
5
404
Data distribution
0
2000
300
325
350
375
400
775
750
725


Strathmore
Calcium (CaO) in Stream Sediments
Percentiles
% CaO
99
95
90
75
50
25
15
10
5
4.272
3.477
3.001
2.424
1.957
1.415
1.039
0.782
0.582
Data distribution
0
7
300
325
350
375
400
775
750
725

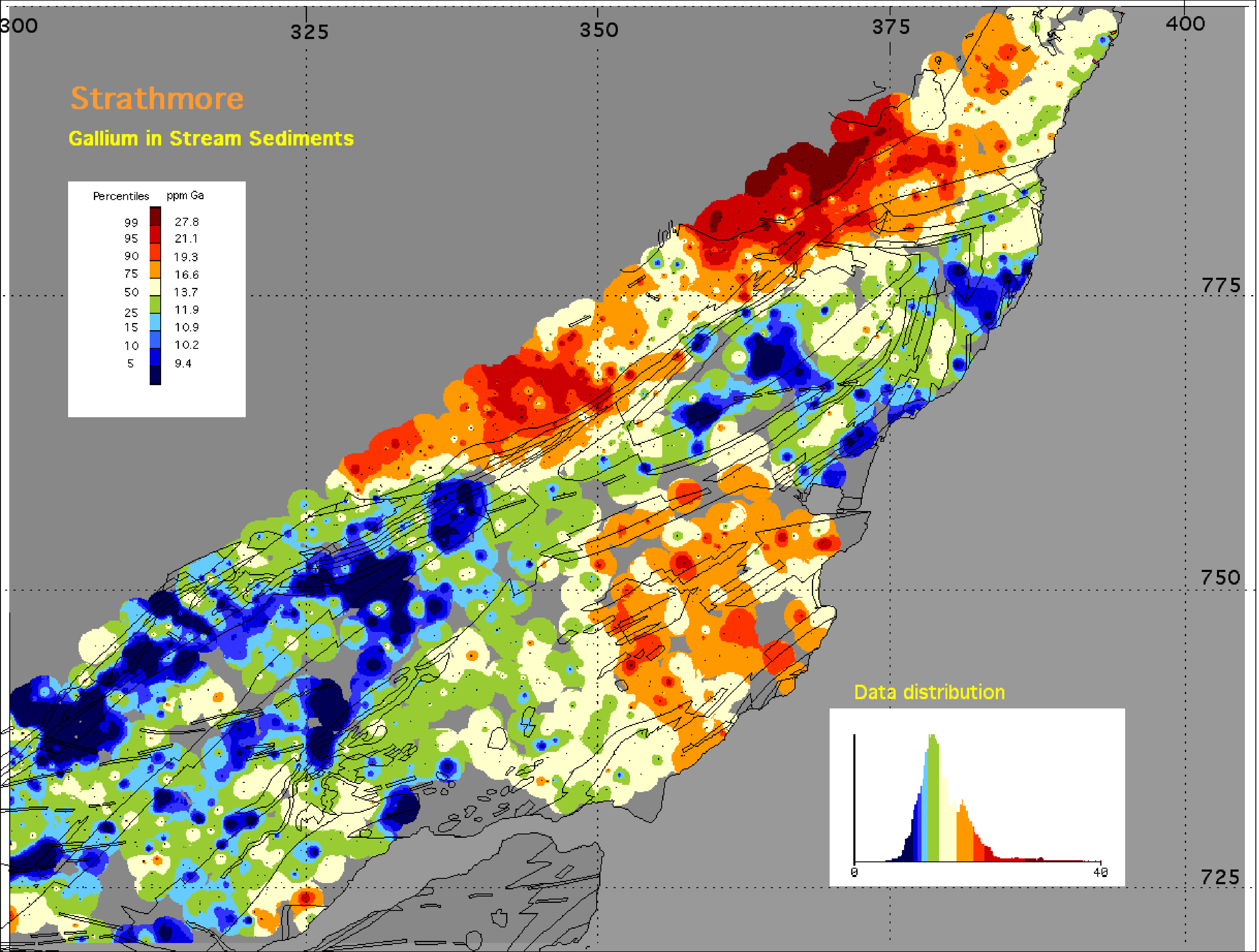


Strathmore
Chromium in Stream Sediments
Percentiles
ppm Cr
99
95
90
75
50
25
15
10
5
456
310
262
209
158
95
81
75
63
Data distribution
0
800
300
325
350
375
400
775
750
725

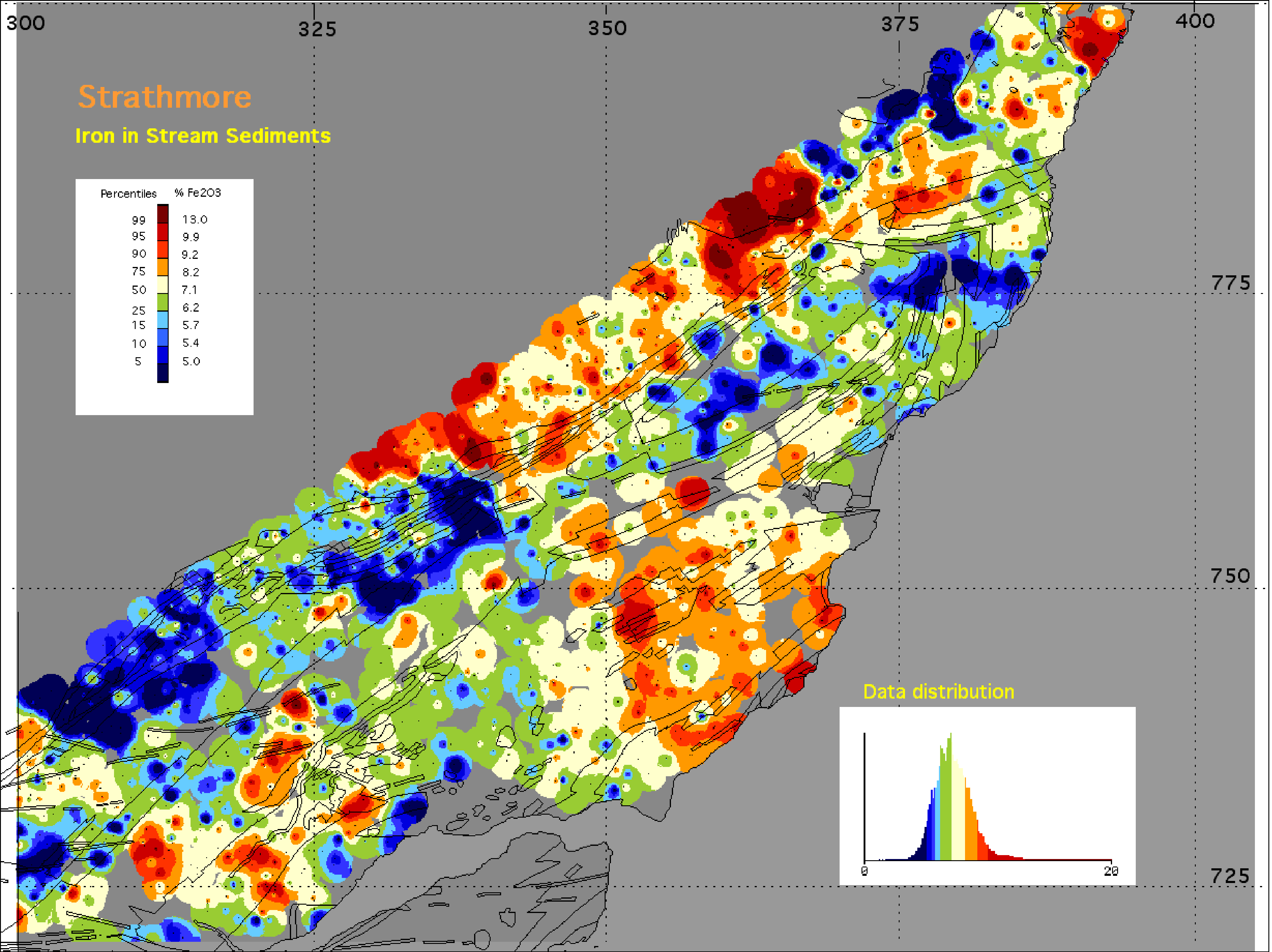

Strathmore
Cobalt in Stream Sediments
Percentiles ppm Co
99 61
95 38
90 28
75 22
50 18
25 14
15 12
10 11
5 10
Data distribution
0
100
300
325
350
375
400
775
750
725

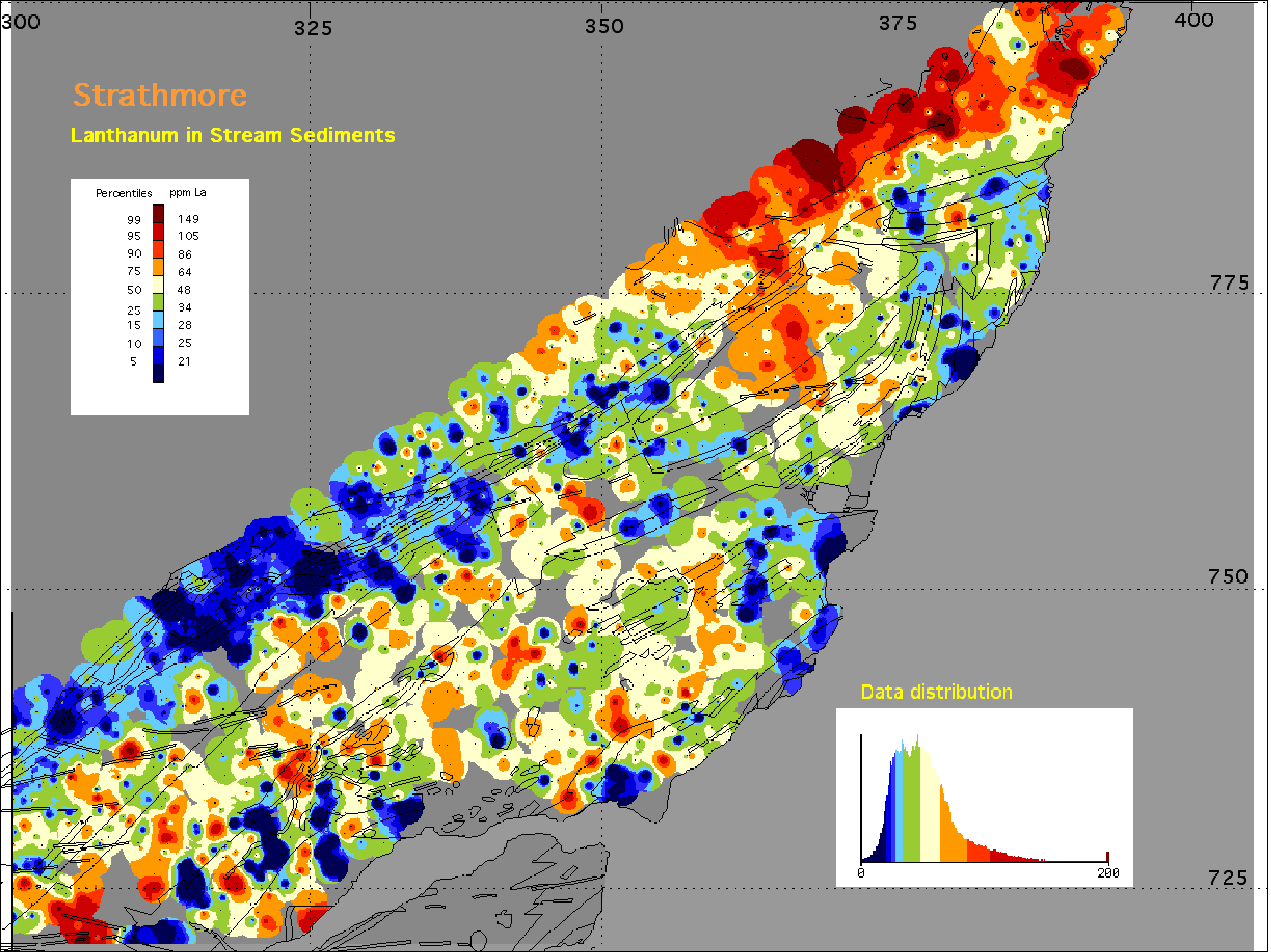


300
325
350
375
400
775
750
725
Strathmore
Copper in Stream Sediments
Percentiles
ppm Cu
99
95
90
75
50
25
15
10
5
78
56
48
37
30
24
21
19
16
Data distribution
0
200

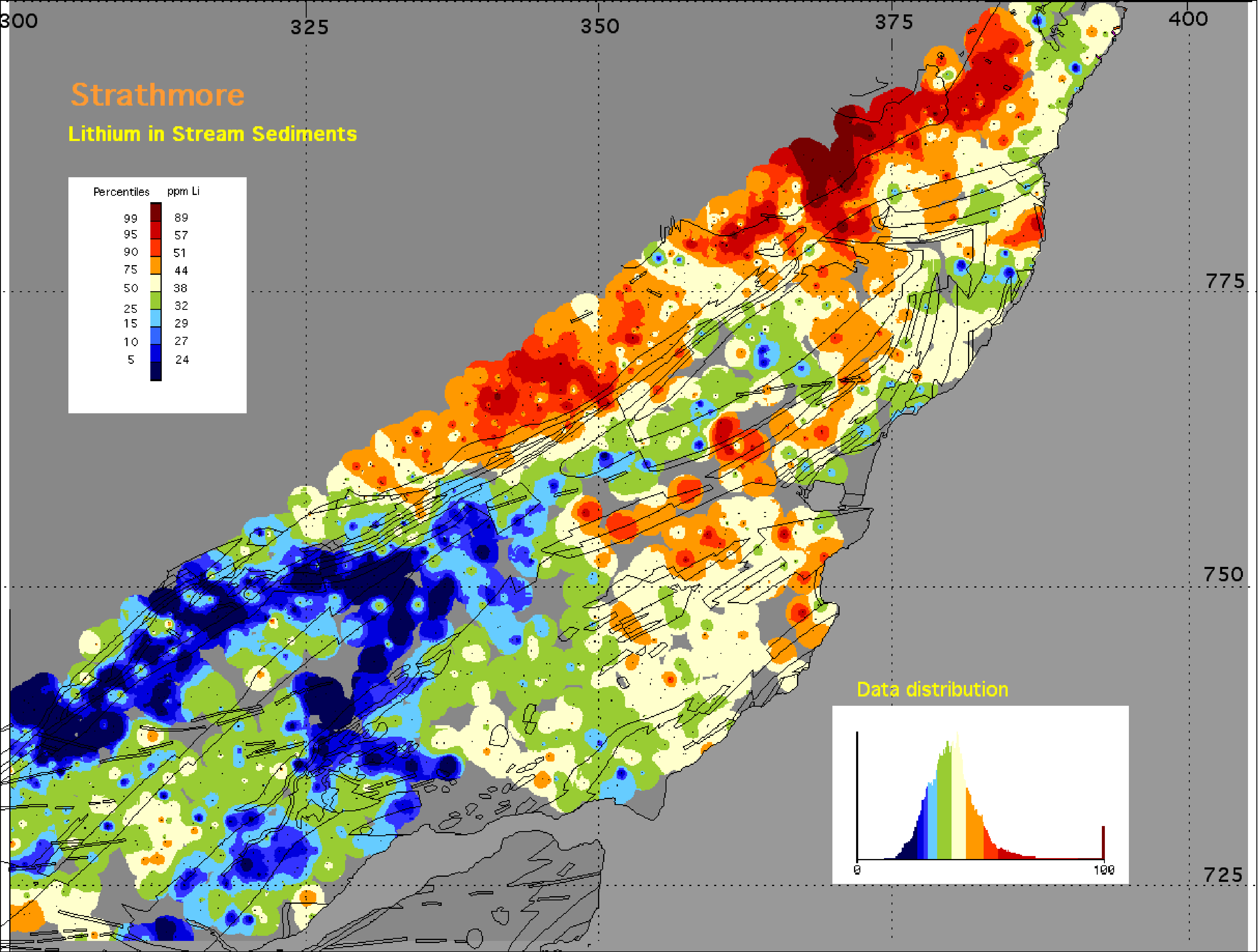


Strathmore
Gallium in Stream Sediments
Percentiles
ppm Ga
99
27.8
95
21.1
90
19.3
75
16.6
50
13.7
25
11.9
15
10.9
10
10.2
5
9.4
Data distribution
0
40
300
325
350
375
400
775
750
725

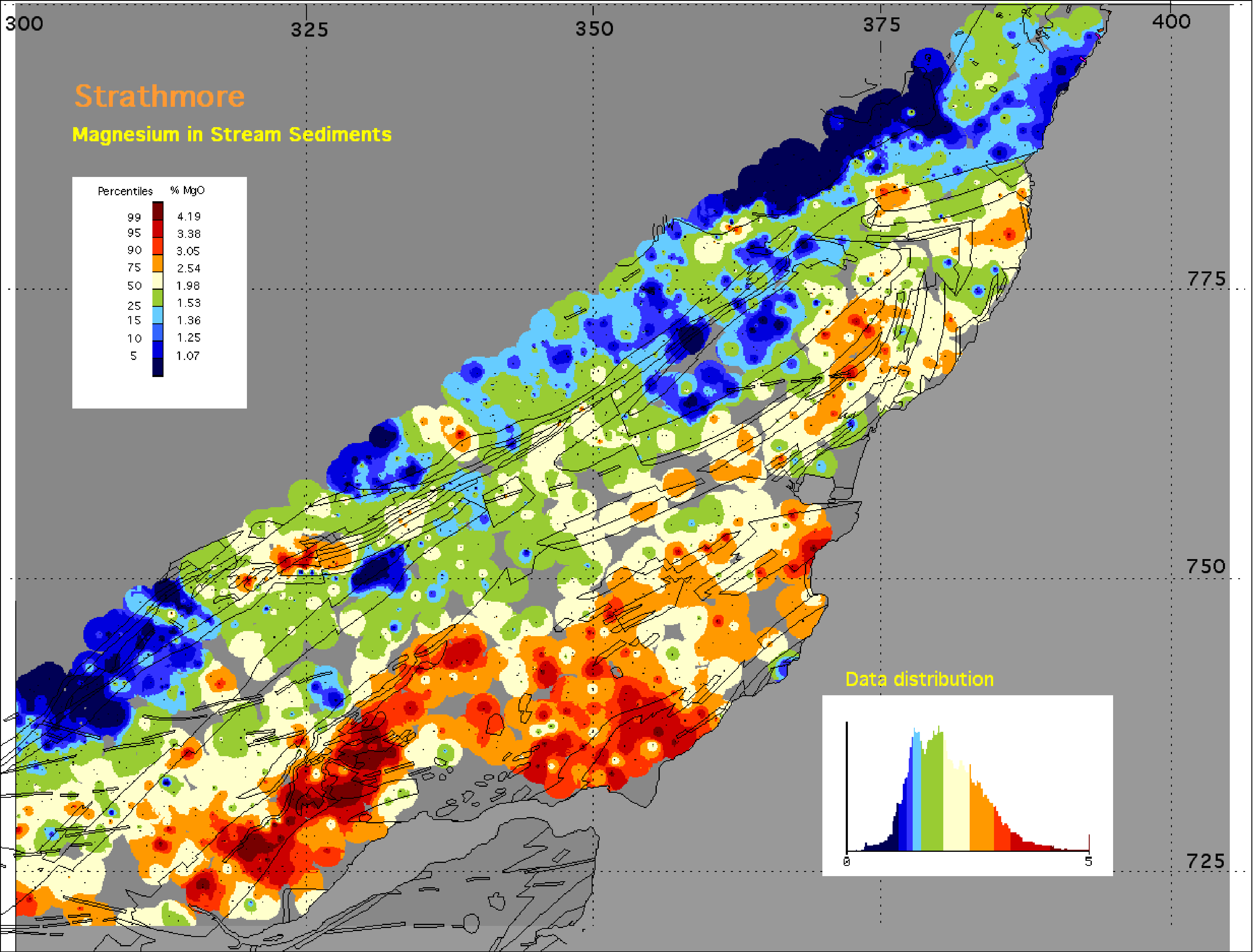

Strathmore
Iron in Stream Sediments
Percentiles
% Fe2O3
99
95
90
75
50
25
15
10
5
13.0
9.9
9.2
8.2
7.1
6.2
5.7
5.4
5.0
Data distribution
0
20
300
325
350
375
400
775
750
725

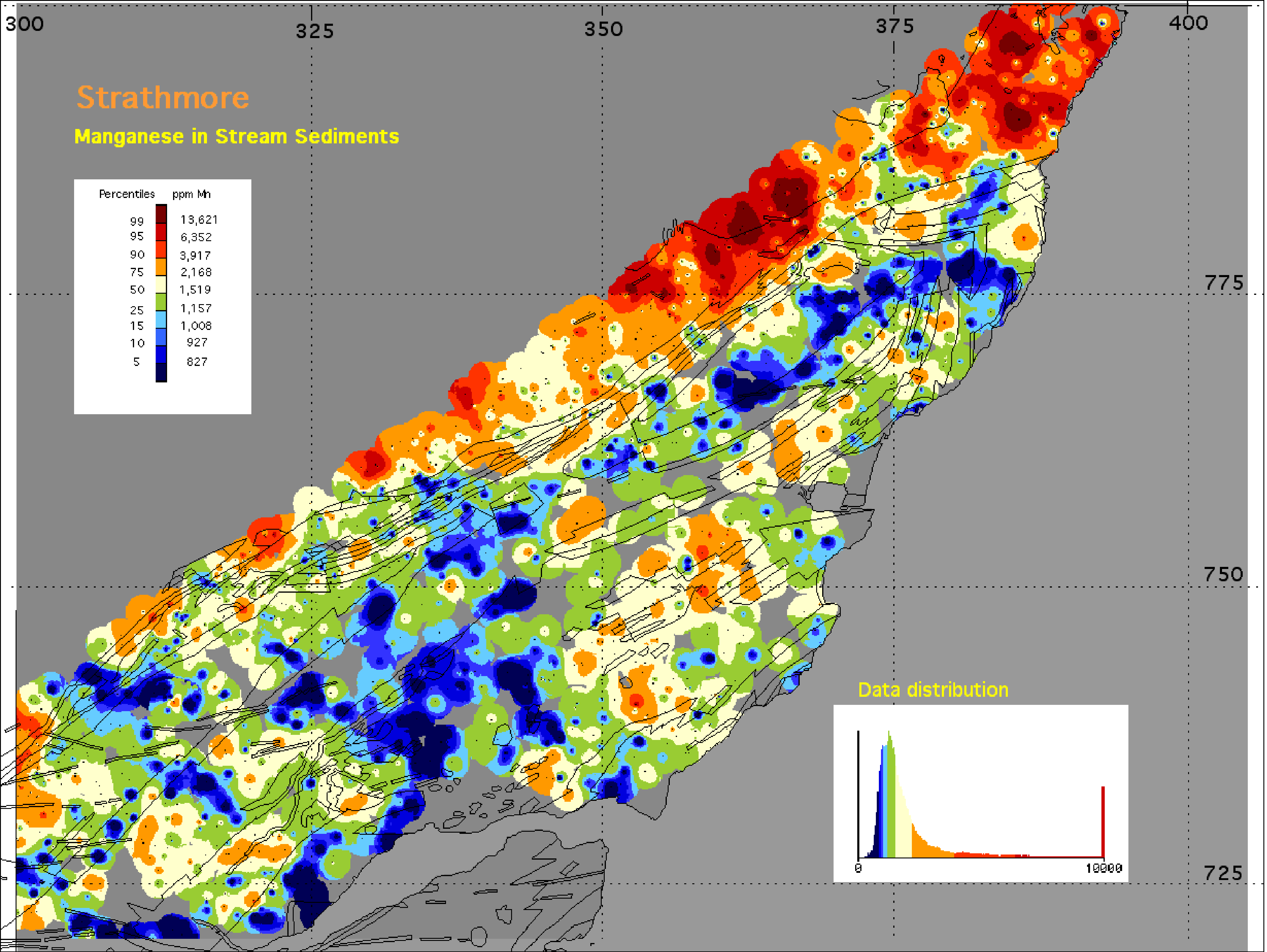


Strathmore
Lanthanum in Stream Sediments
Percentiles
ppm La
99
95
90
75
50
25
15
10
5
149
105
86
64
48
34
28
25
21
Data distribution
0
200
300
325
350
375
400
775
750
725

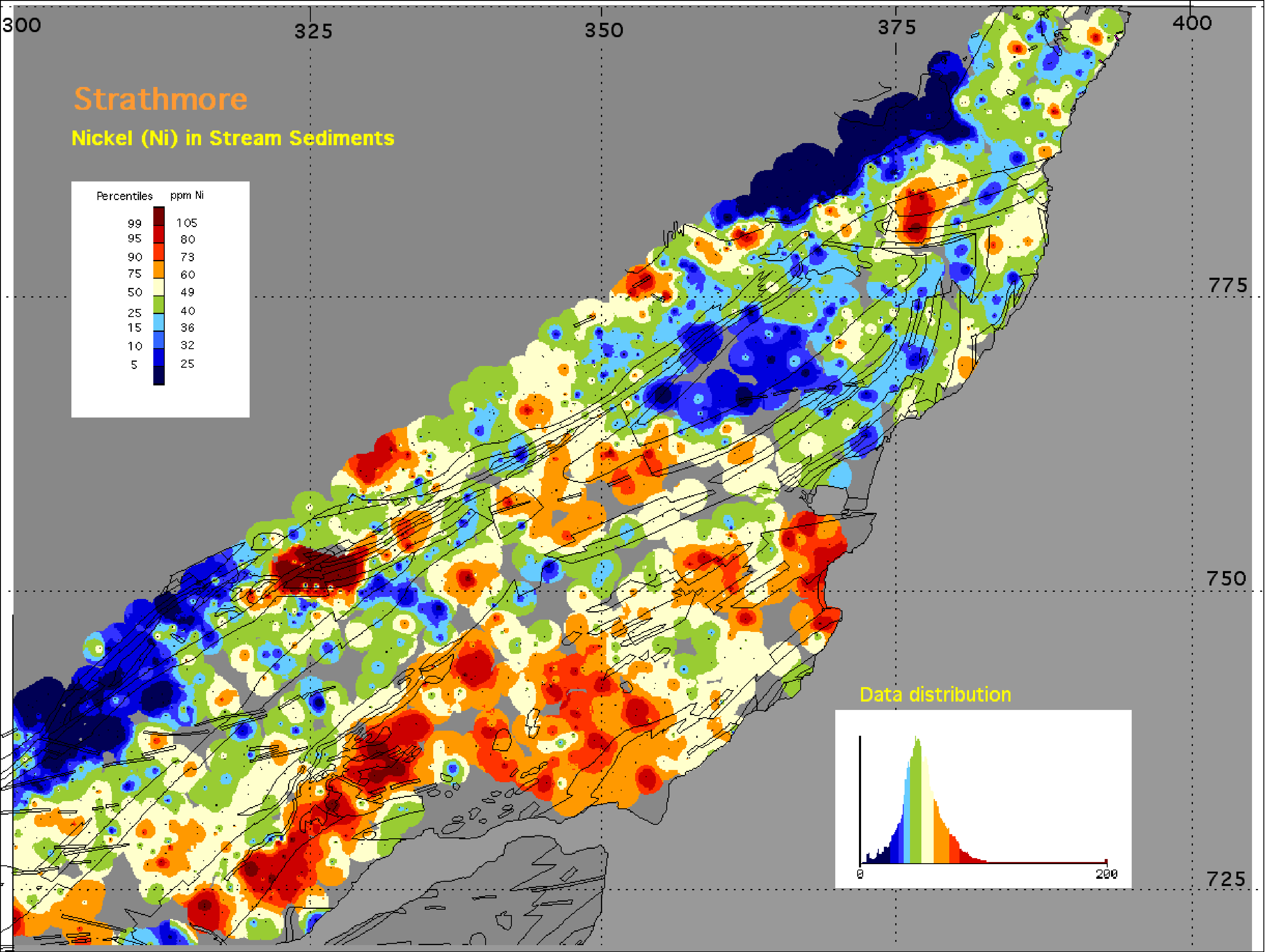


Strathmore
Lithium in Stream Sediments
Percentiles
ppm Li
99
95
90
75
50
25
15
10
5
89
57
51
44
38
32
29
27
24
Data distribution
0
100
300
325
350
375
400
775
750
725

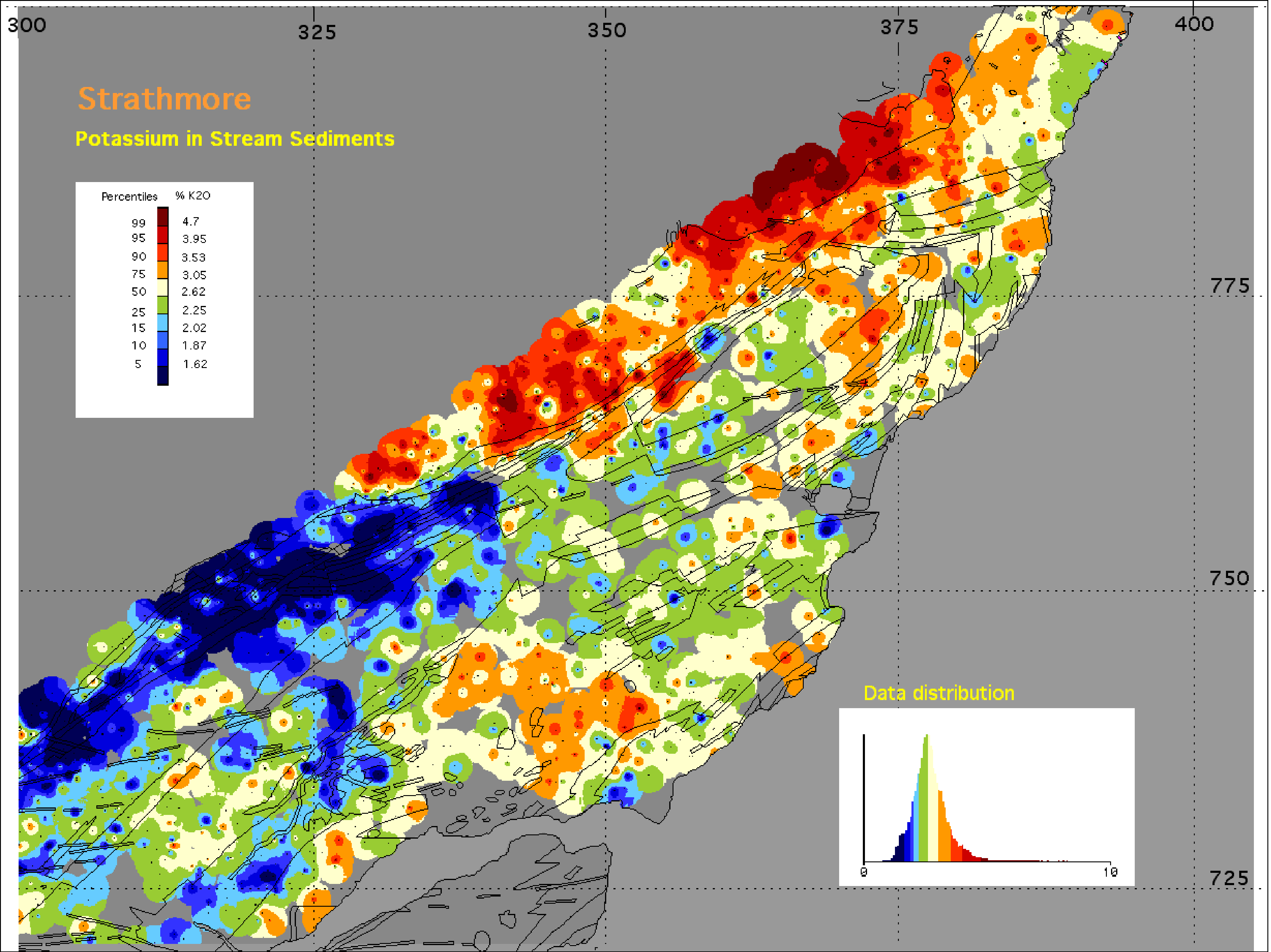

Strathmore
Magnesium in Stream Sediments
Percentiles
% MgO
99
4.19
95
3.38
90
3.05
75
2.54
50
1.98
25
1.53
15
1.36
10
1.25
5
1.07
Data distribution
0
5
300
325
350
375
400
775
750
725



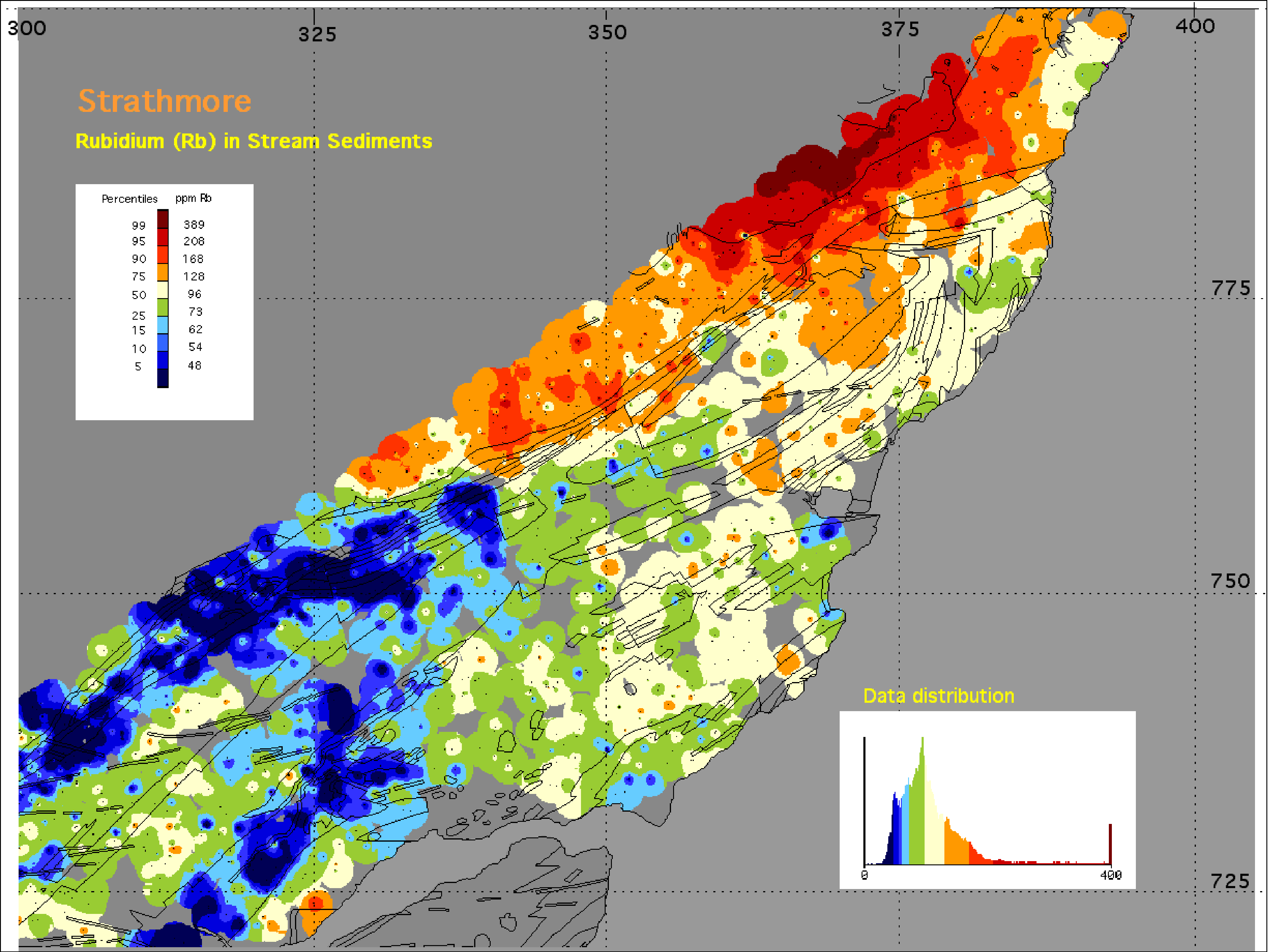
Strathmore
Manganese in Stream Sediments
Percentiles
ppm Mn
99
13,621
95
6,352
90
3,917
75
2,168
50
1,519
25
1,157
15
1,008
10
927
5
827
300
325
350
375
400
775
750
725
Data distribution
0
10000

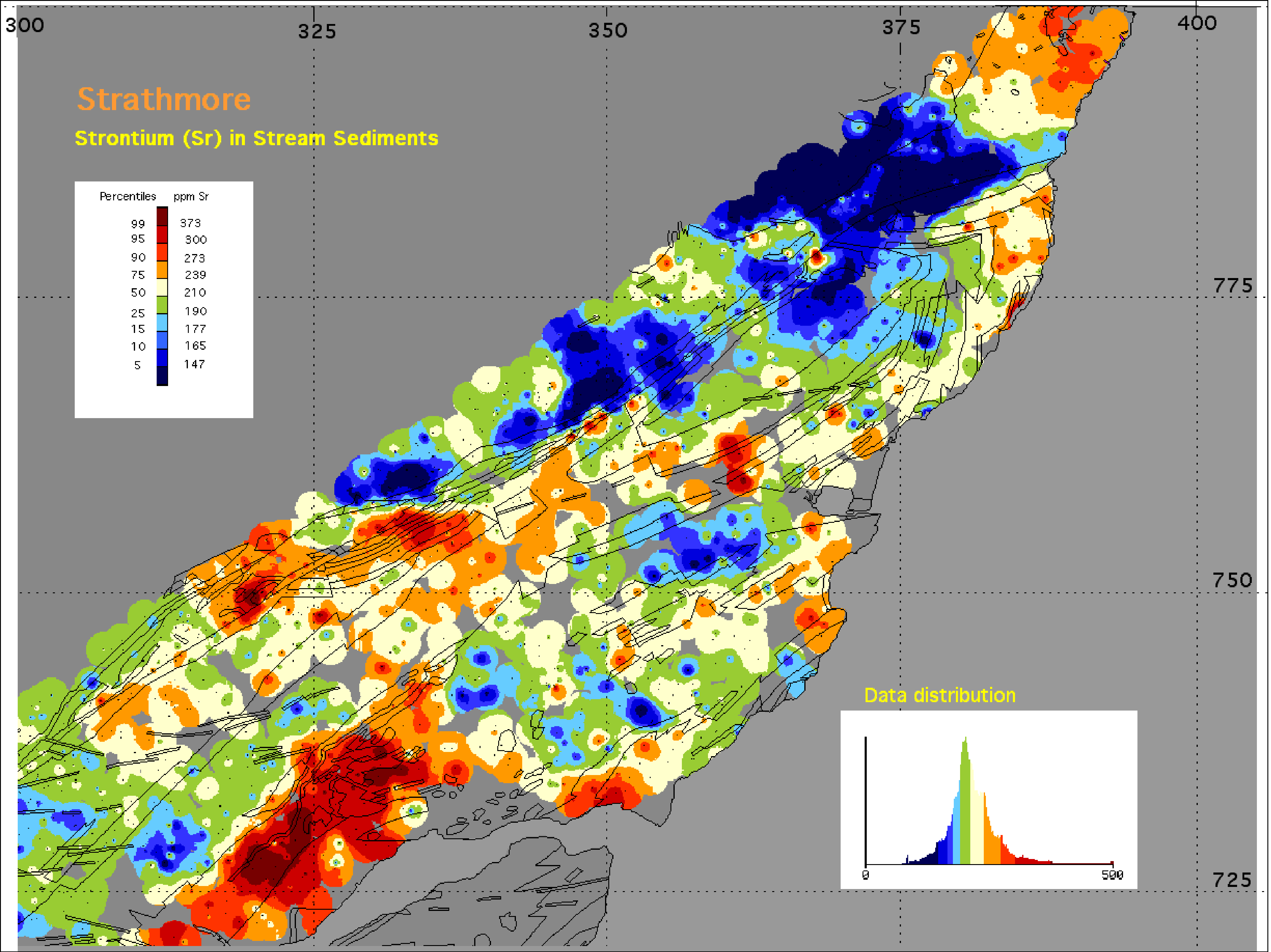


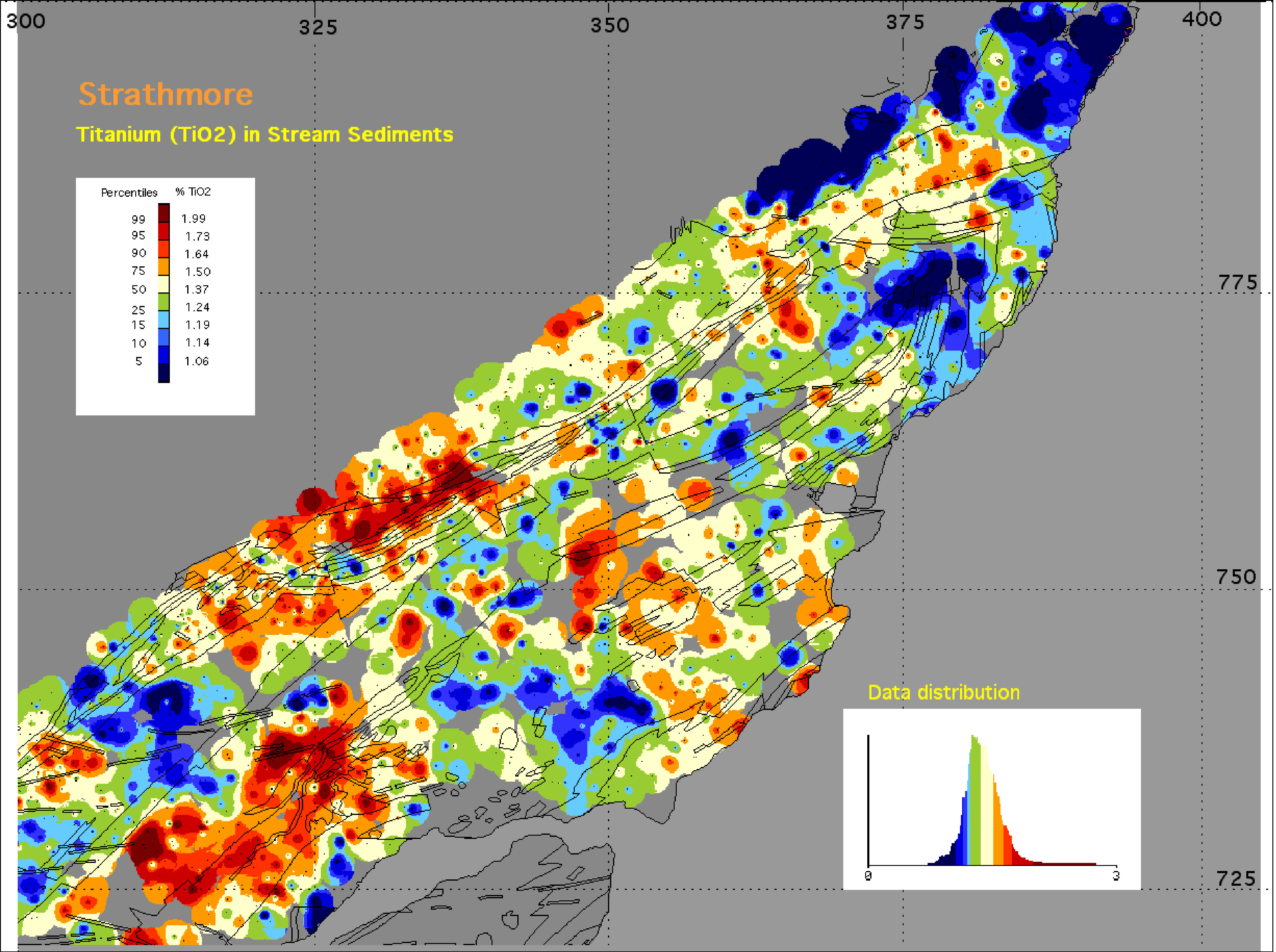
300
325
350
375
400
Strathmore
Nickel (Ni) in Stream Sediments
Percentiles
ppm Ni
99 105
95 80
90 73
75 60
50 49
25 40
15 36
10 32
5 25
775
750
725
Data distribution
0
200

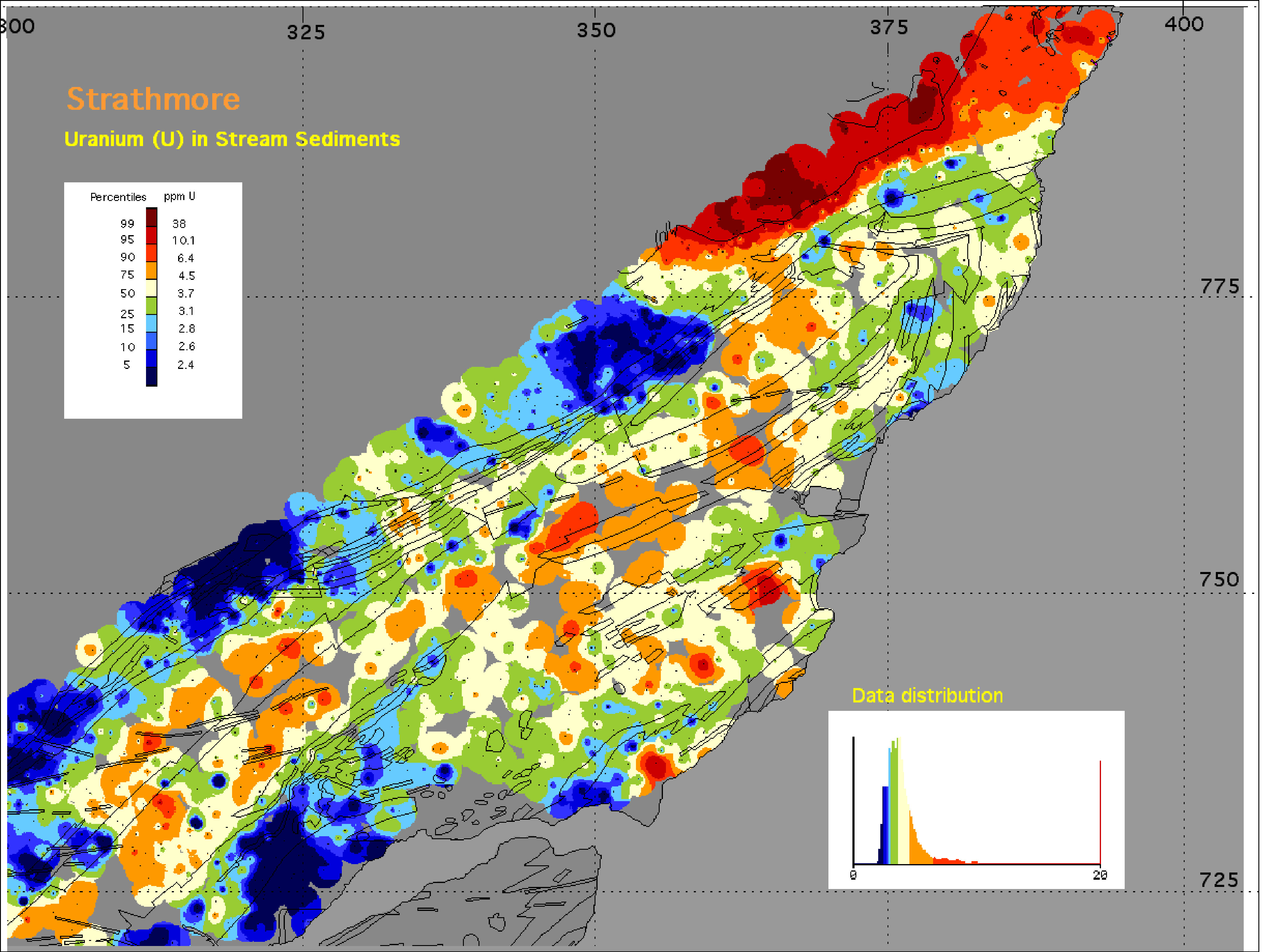


Strathmore
Potassium in Stream Sediments
Percentiles % K2O
99 4.7
95 3.95
90 3.53
75 3.05
50 2.62
25 2.25
15 2.02
10 1.87
5 1.62
300
325
350
375
400
775
750
725
Data distribution
0
10

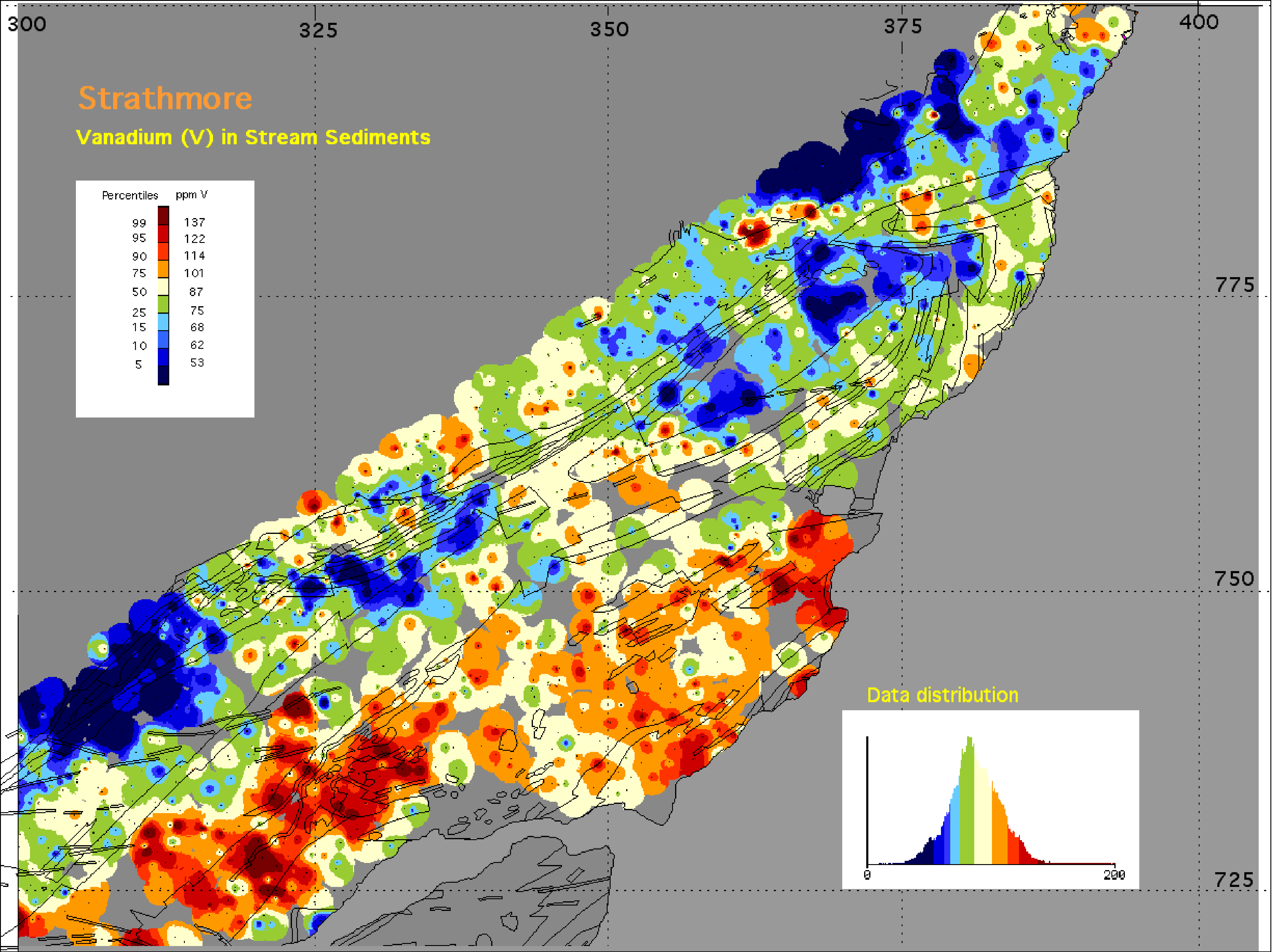

Strathmore
Rubidium (Rb) in Stream Sediments
Percentiles
ppm Rb
99 389
95 208
90 168
75 128
50 96
25 73
15 62
10 54
5 48
Data distribution
0
400
300
325
350
375
400
775
750
725


300
325
350
375
400
775
750
725
Strathmore
Strontium (Sr) in Stream Sediments
Percentiles
ppm Sr
99
373
95
300
90
273
75
239
50
210
25
190
15
177
10
165
5
147
Data distribution
0
500

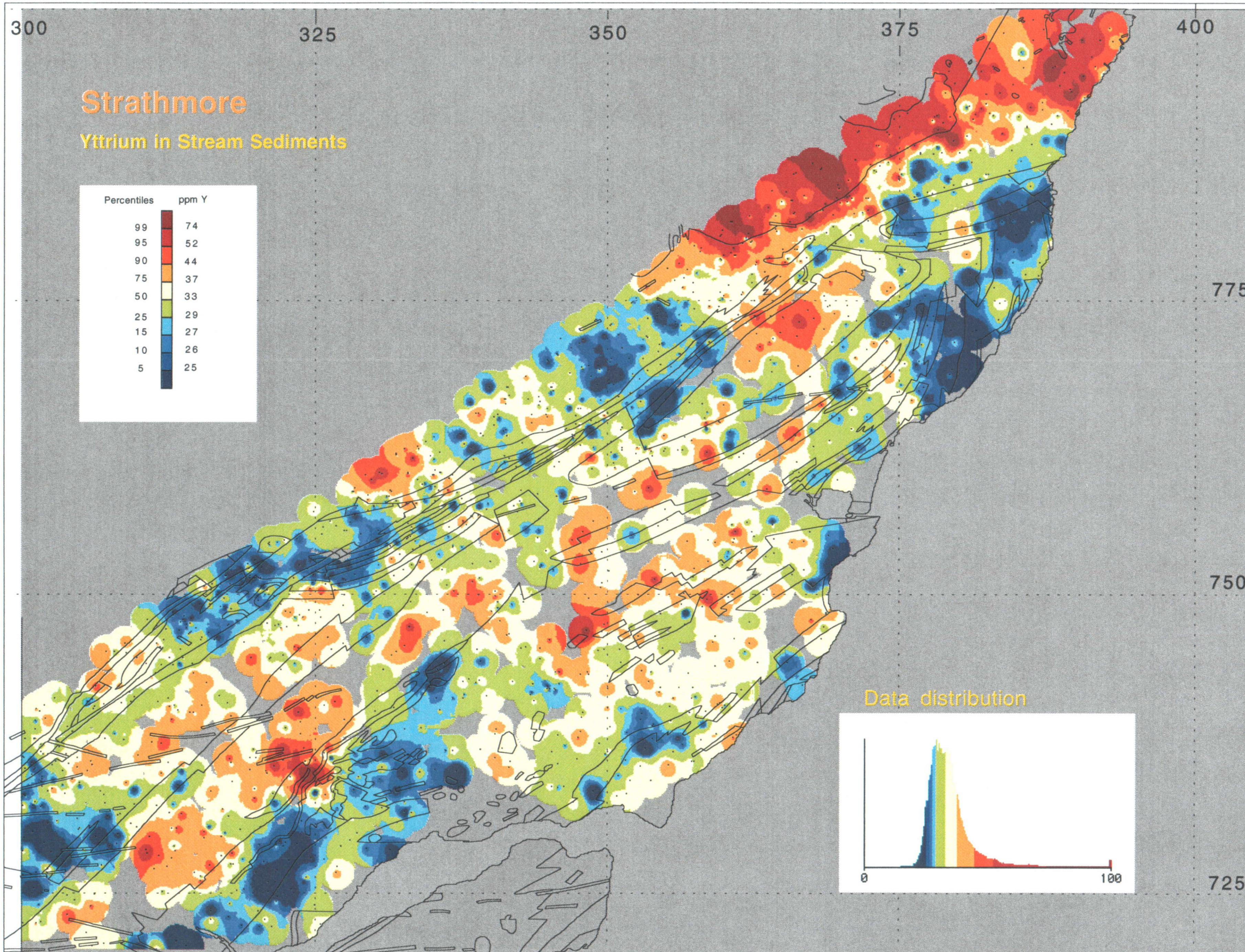

Strathmore
Titanium (TiO2) in Stream Sediments
Percentiles
% TiO2
99
95
90
75
50
25
15
10
5
1.99
1.73
1.64
1.50
1.37
1.24
1.19
1.14
1.06
Data distribution
0
3
300
325
350
375
400
775
750
725



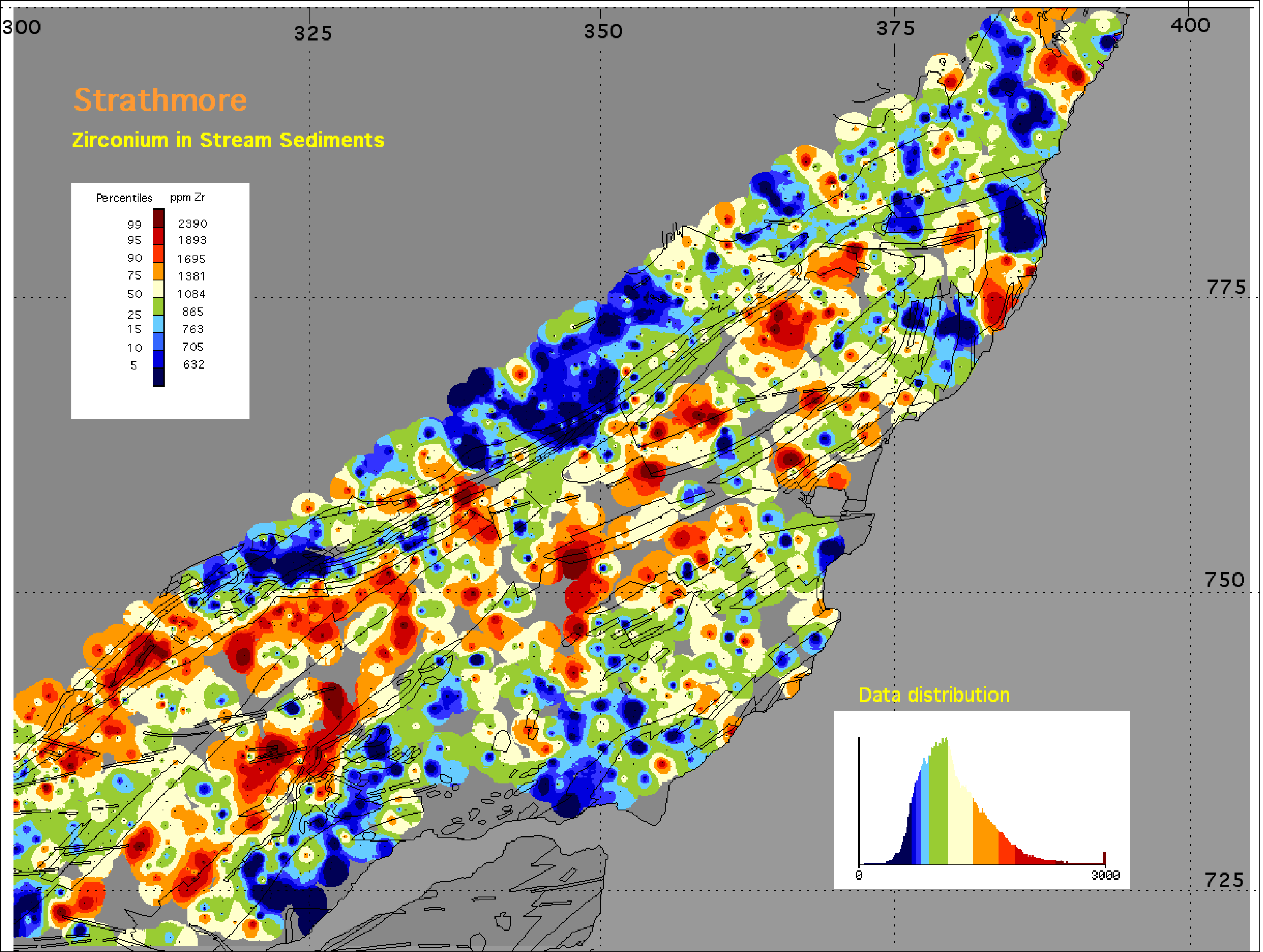
Strathmore
Uranium (U) in Stream Sediments
Percentiles
ppm U
99
38
95
10.1
90
6.4
75
4.5
50
3.7
25
3.1
15
2.8
10
2.6
5
2.4
Data distribution
0
20
300
325
350
375
400
775
750
725



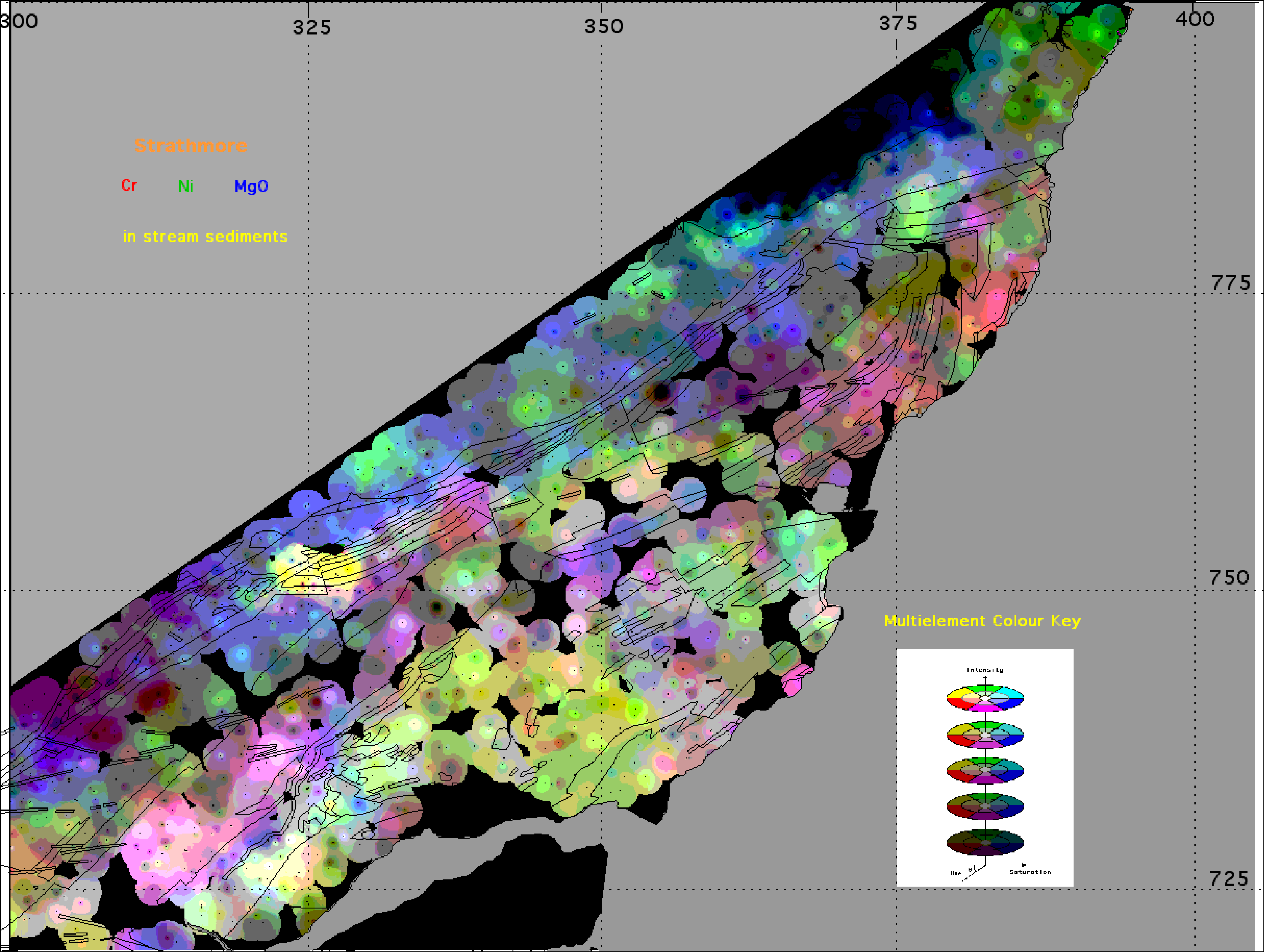
Strathmore
Vanadium (V) in Stream Sediments
Percentiles
ppm V
99
137
95
122
90
114
75
101
50
87
25
75
15
68
10
62
5
53
300
325
350
375
400
775
750
725
Data distribution
0
200



Strathmore
Yttrium in Stream Sediments
Percentiles
ppm Y
99 74
95 52
90 44
75 37
50 33
25 29
15 27
10 26
5 25
Data distribution
0
100
300
325
350
375
400
775
750
725



Strathmore
Zirconium in Stream Sediments
Percentiles
ppm Zr
99 2390
95 1893
90 1695
75 1381
50 1084
25 865
15 763
10 705
5 632
Data distribution
0
3000
300
325
350
375
400
775
750
725



300
325
350
375
400
775
750
725
Strathmore
Cr
Ni
MgO
in stream sediments
Multielement Colour Key