Soil geochemistry of northwest Victoria, Australia: mapping the environmental baseline of Murray Basin critical minerals

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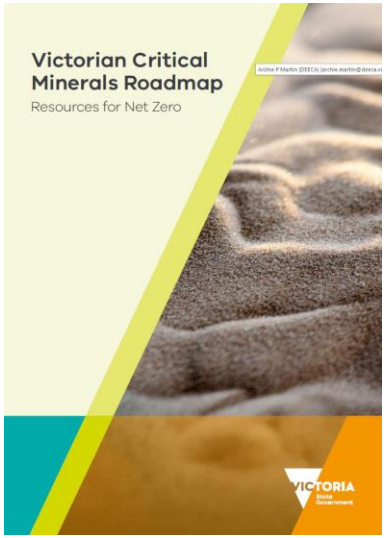
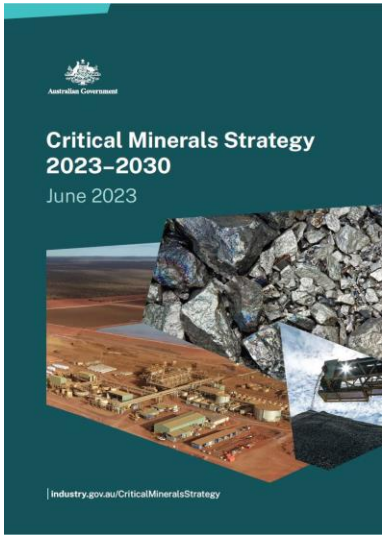
Victorian Roadmap



Australian Critical Minerals Strategy



UN Sustainability Goals

Relevance

Memorandum of understanding between th European Union and Australia on strategic partnership on a sustainable critical and strategic minerals

Date published: 28 May 2024

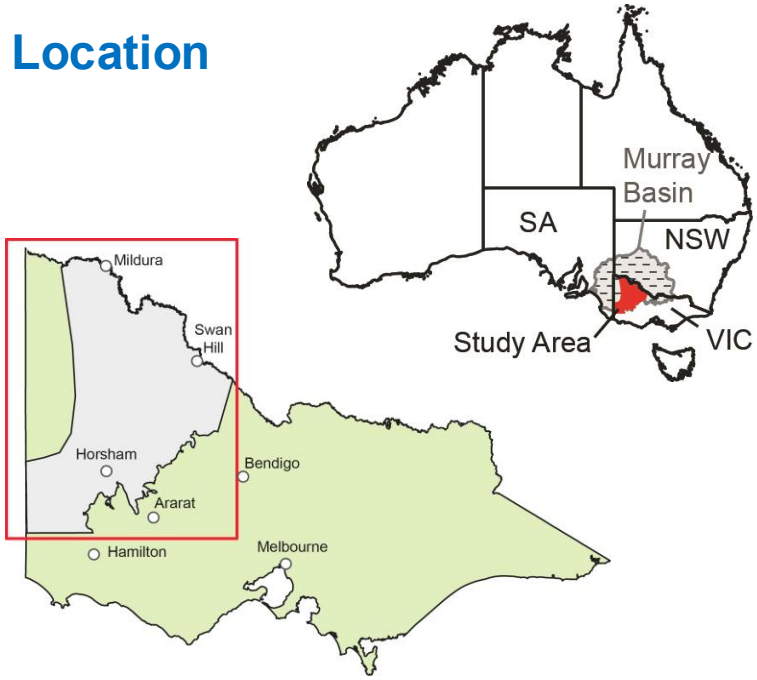
Australian Government
Department of Industry, Science and Resources

The strategy projects significant economic gains from downstream processing, including a potential **AUD 139.7 billion in GDP** and **262,600 jobs by 2040**.

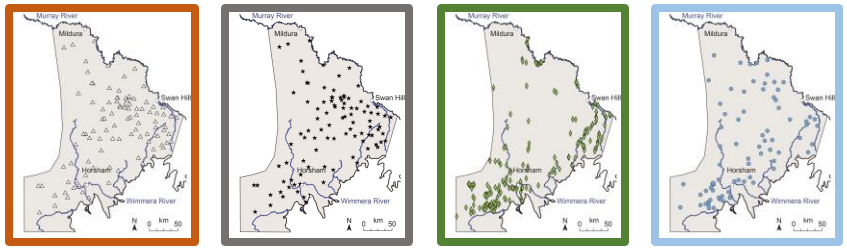
Aims

- Provide a common set of data as an evidence base for evaluation, further studies and monitoring: **Multi-element environmental geochemical baseline**
- Establish if the presence of mineral sands, and the critical minerals contained within, can be detected in the natural geochemistry of the region: **REE + TiO_2 + Zr**

Location

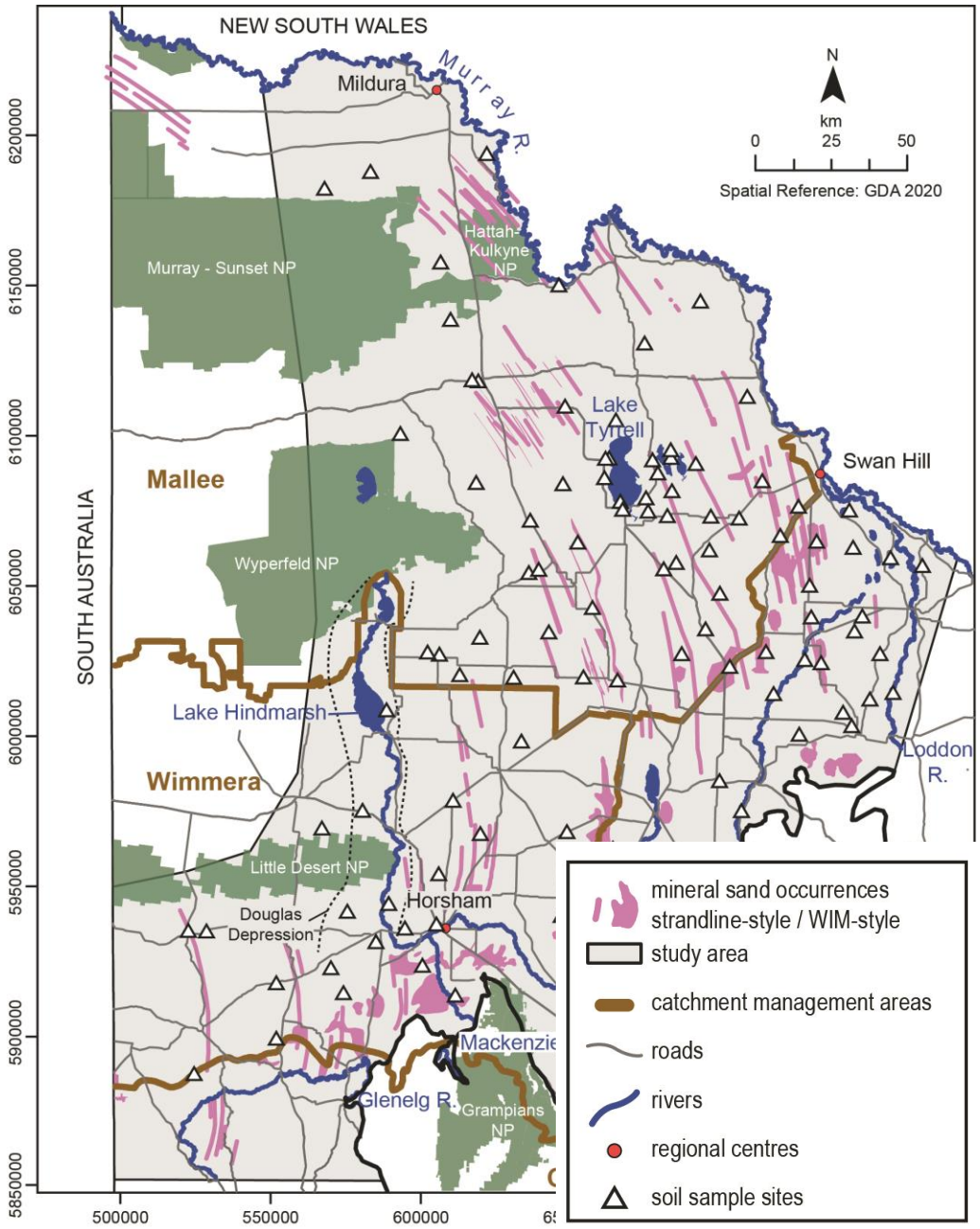


Soil **Groundwater**

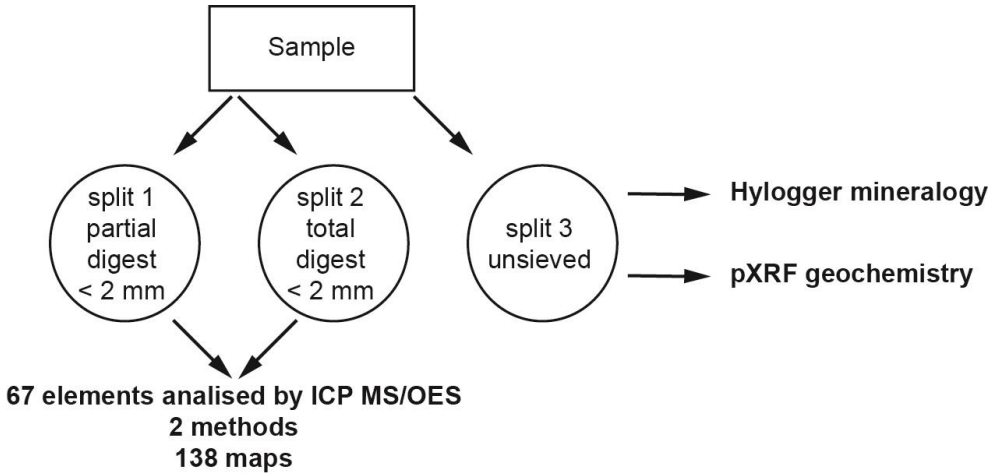


Vegetation **Lake Sediment, Salt**

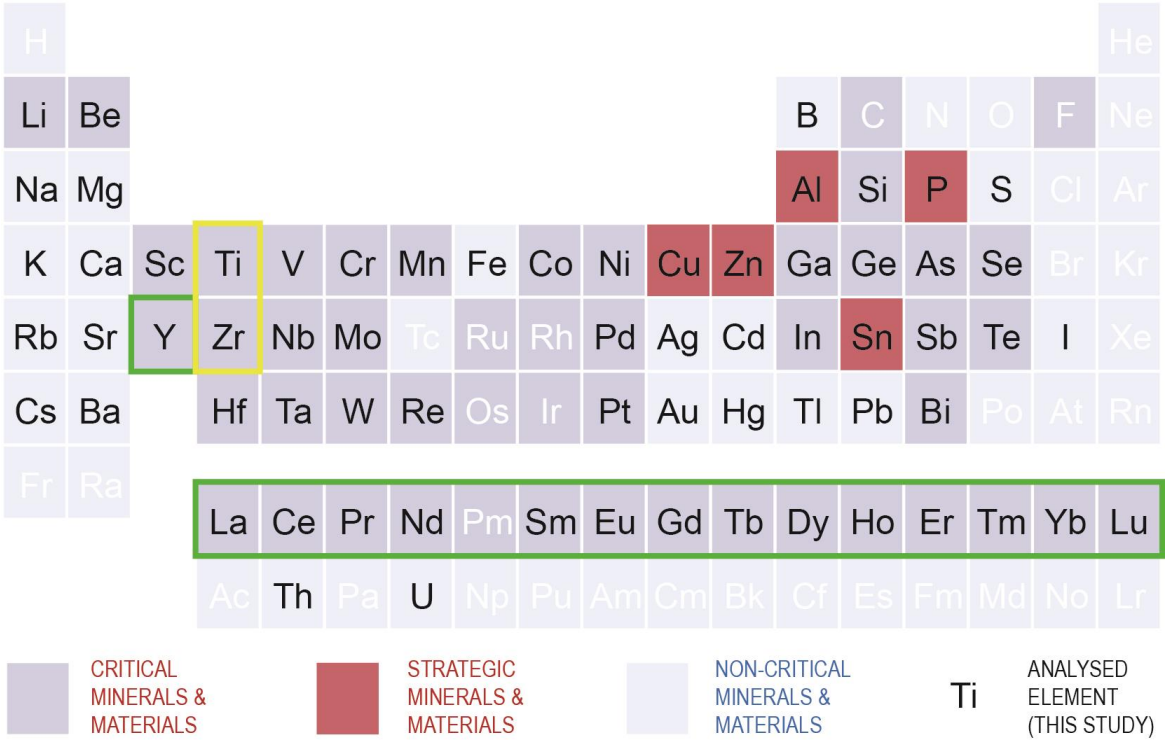
Parilla Sand



Soil Sample Preparation



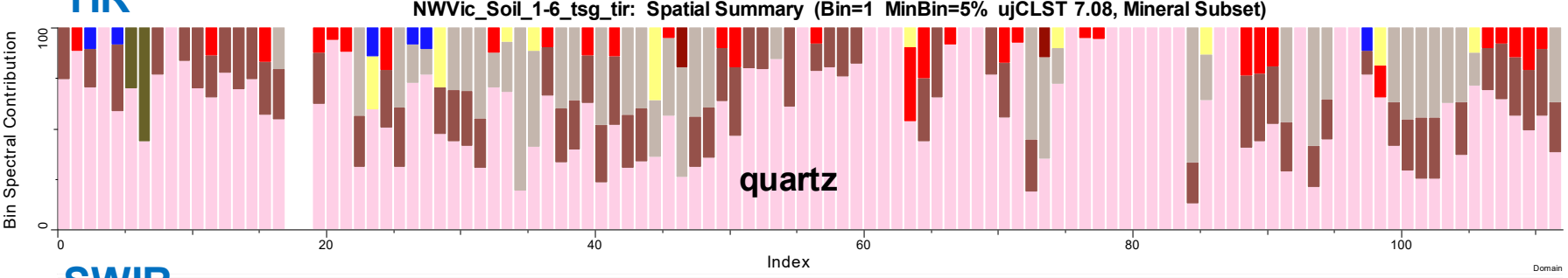
Elements Analysed in Soil



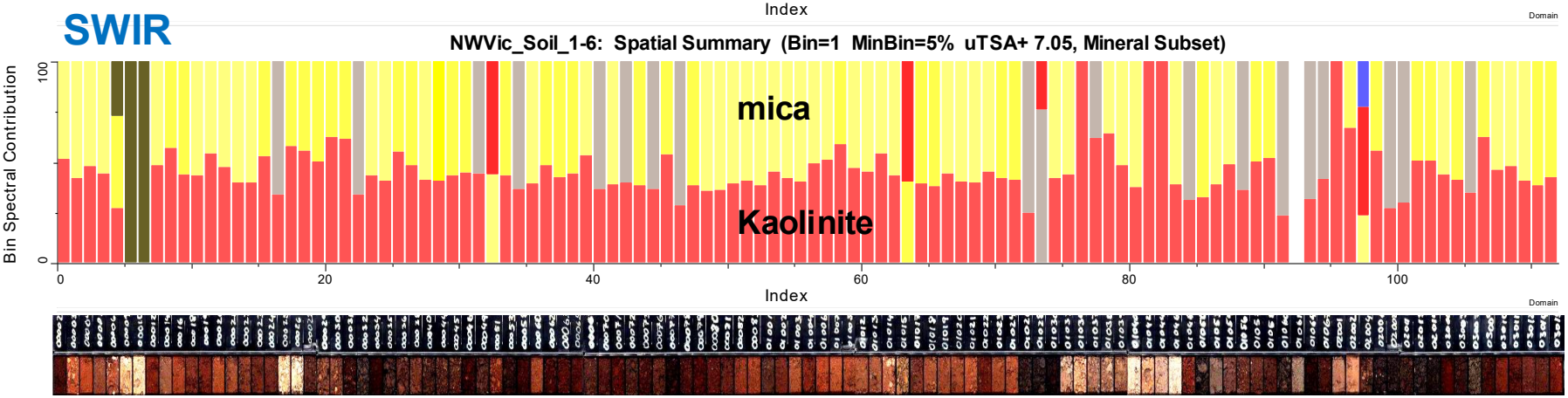
REE + TiO_2 + Zr

HyLogger mineral match with TIR or SWIR library

TIR

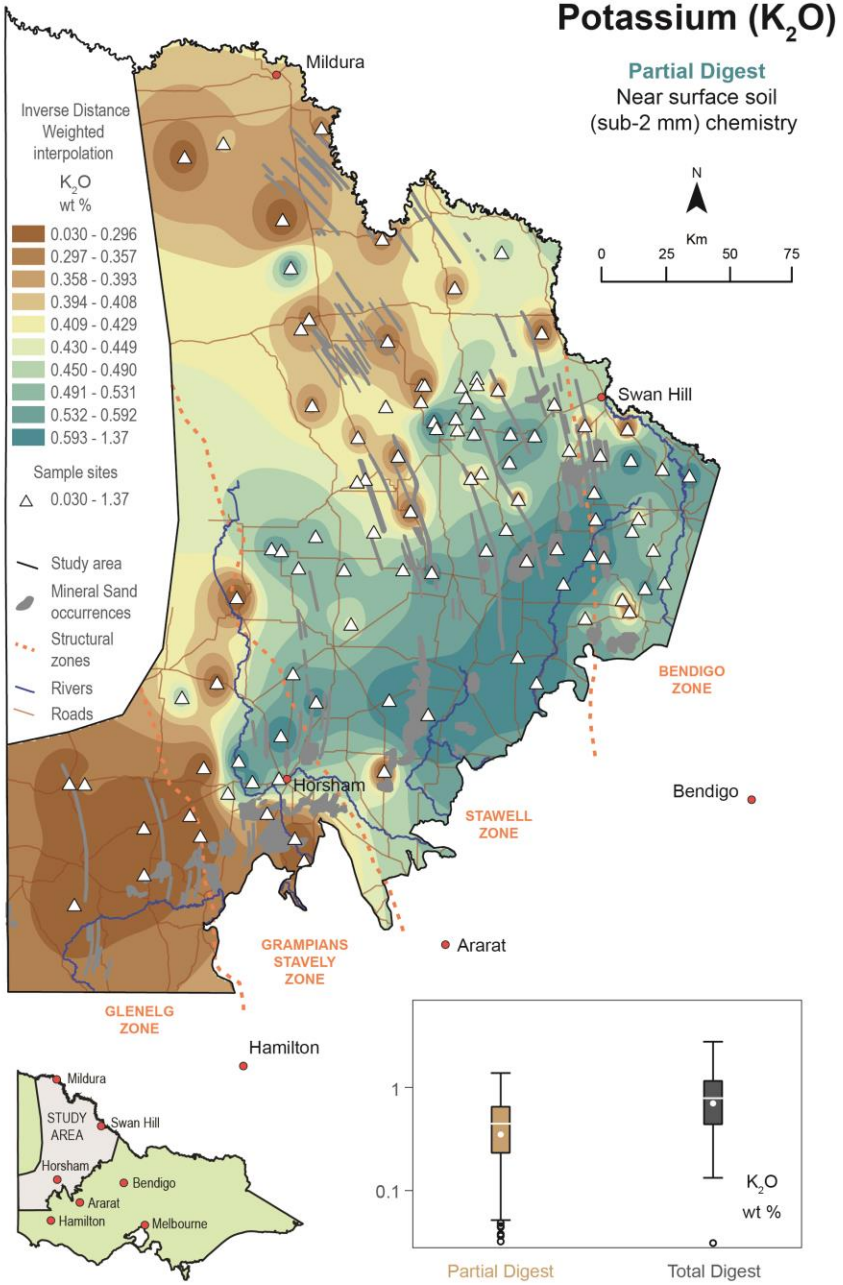


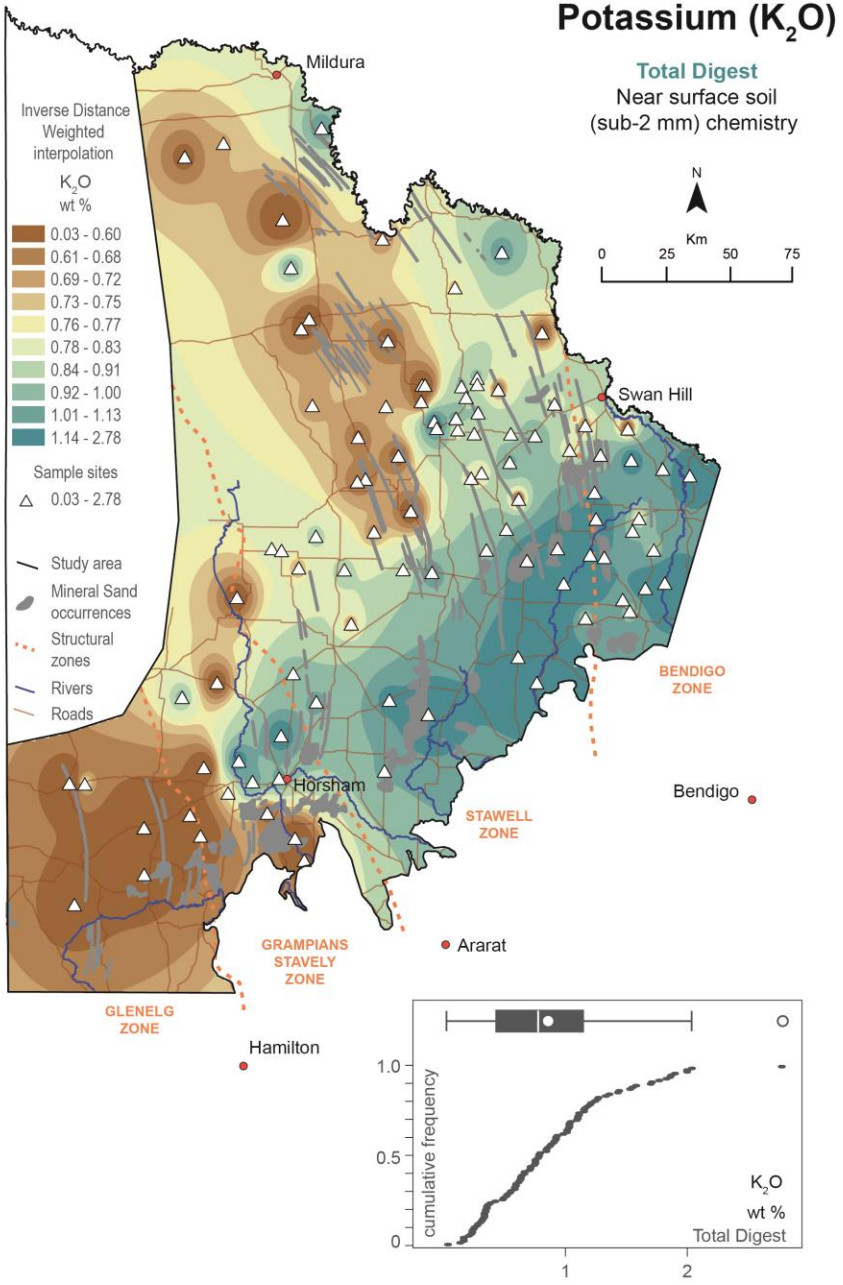
SWIR



Thermal infrared (TIR): quartz ± kaolinite (crystalline/non-crystalline) ± feldspar ± gypsum ± calcite ± other clay

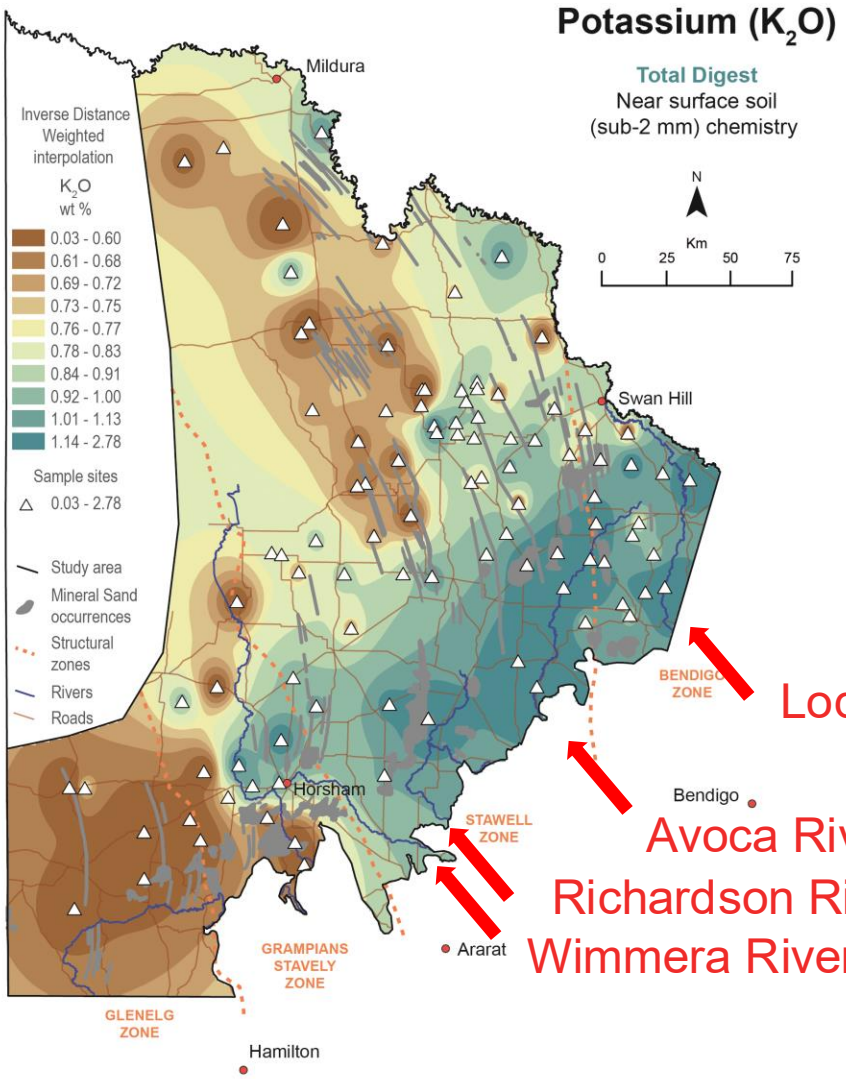
Shortwave infrared (SWIR): kaolinite & mica


Potassium (K_2O)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
K_2O wt %
0.030 - 0.296
0.297 - 0.357
0.358 - 0.393
0.394 - 0.408
0.409 - 0.429
0.430 - 0.449
0.450 - 0.490
0.491 - 0.531
0.532 - 0.592
0.593 - 1.37
Sample sites
0.030 - 1.37
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75
Km
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
1
0.1
K_2O wt %
Partial Digest
Total Digest


Potassium (K_2O)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
K_2O wt %
0.03 - 0.60
0.61 - 0.68
0.69 - 0.72
0.73 - 0.75
0.76 - 0.77
0.78 - 0.83
0.84 - 0.91
0.92 - 1.00
1.01 - 1.13
1.14 - 2.78
Sample sites
0.03 - 2.78
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75
Km
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
1.0
0.5
0
cumulative frequency
K_2O wt %
Total Digest
1
2

Low concentration

High concentration



River Flow Direction

Loddon River

Avoca River

Richardson River

Wimmera River

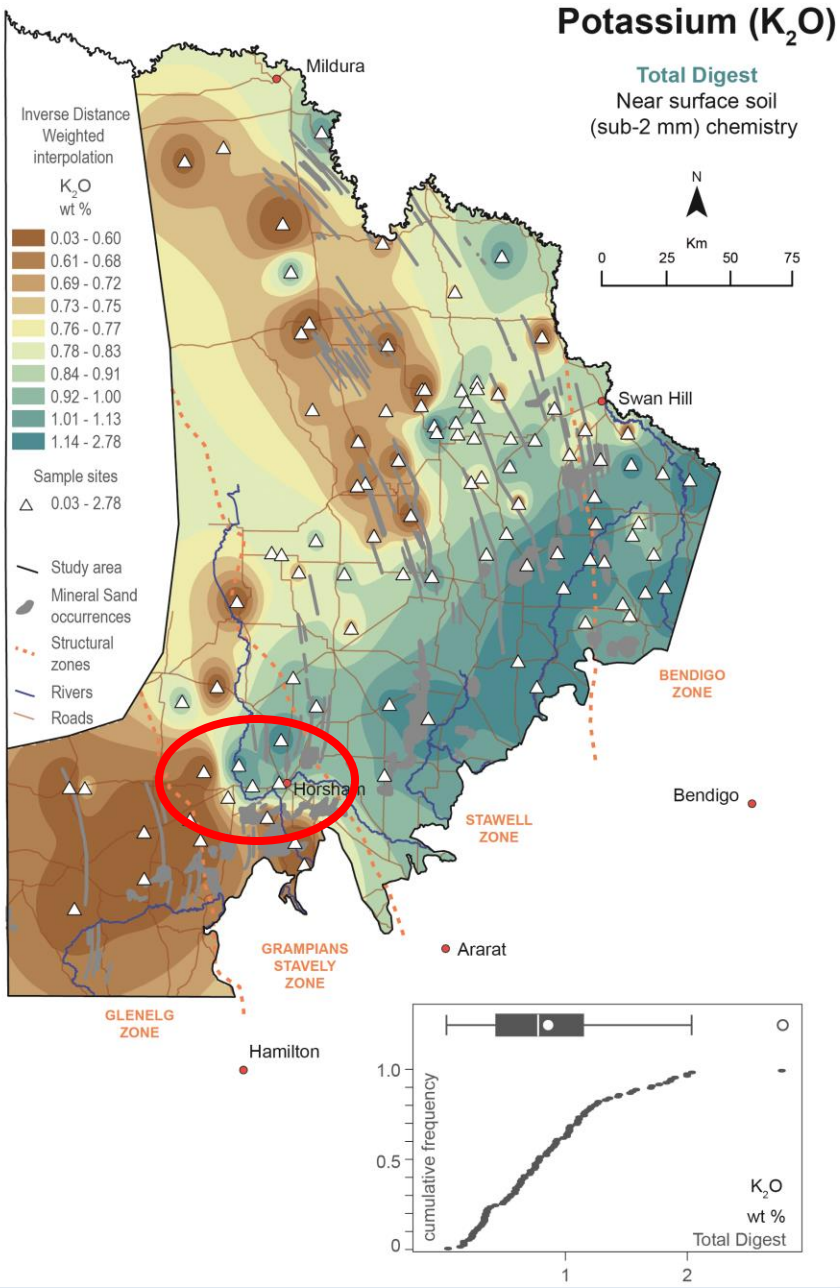
BASEMENT

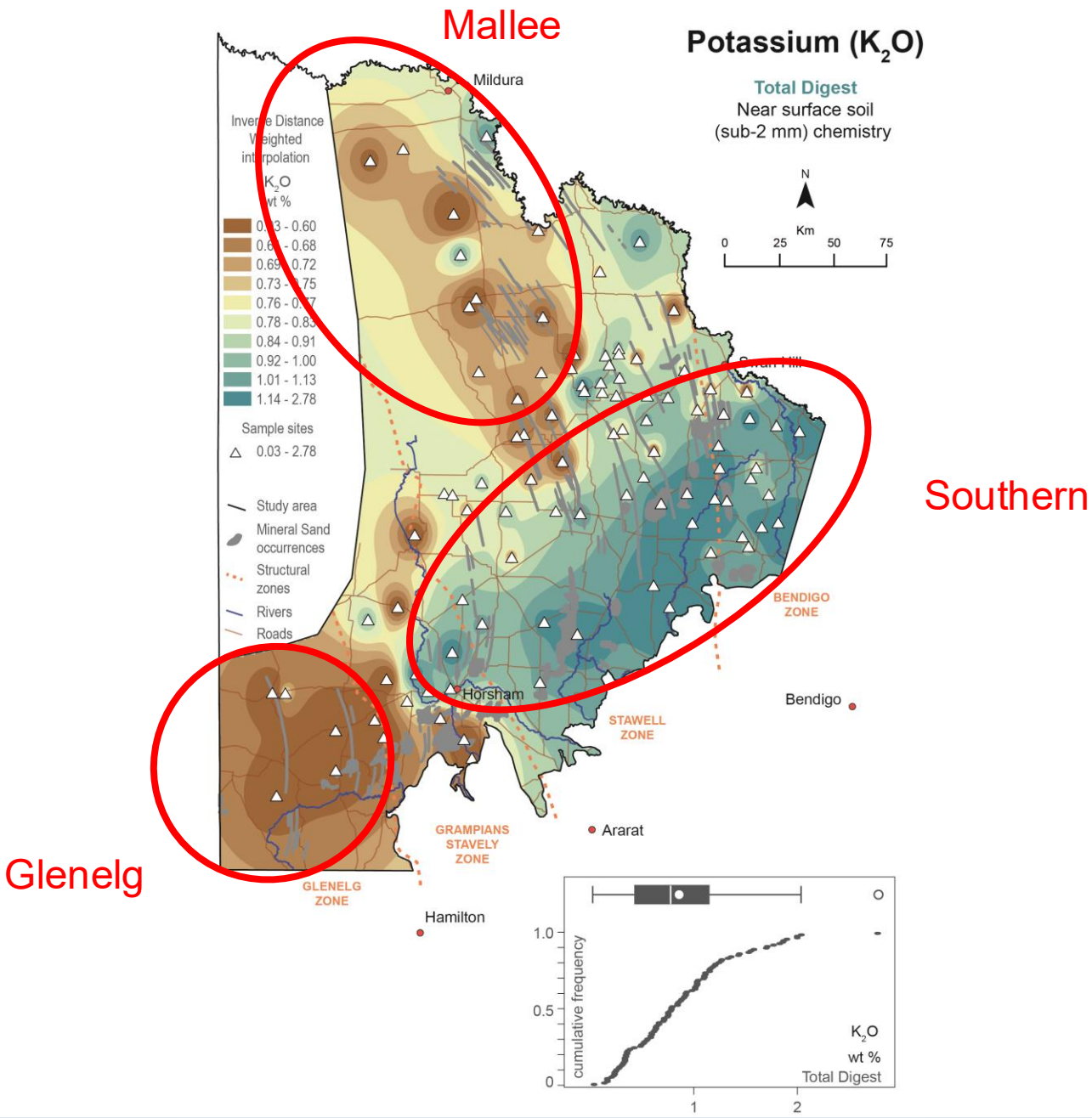
Glenelg Zone

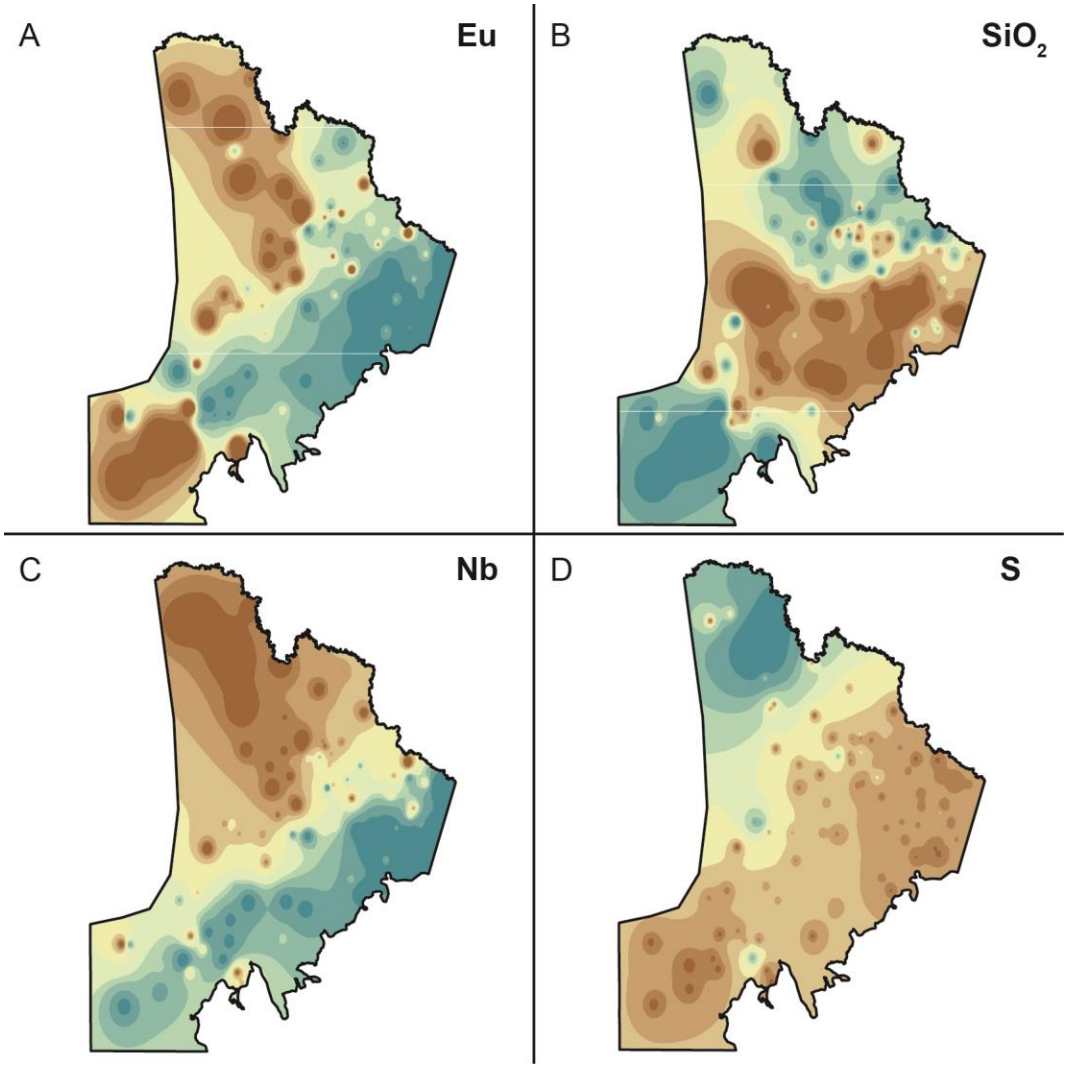
Grampians Stavely Zone

Stawell Zone

Bendigo Zone


Potassium (K_2O)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
K_2O wt %
0.03 - 0.60
0.61 - 0.68
0.69 - 0.72
0.73 - 0.75
0.76 - 0.77
0.78 - 0.83
0.84 - 0.91
0.92 - 1.00
1.01 - 1.13
1.14 - 2.78
Sample sites
0.03 - 2.78
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0
25
50
75
Mildura
Swan Hill
BENDIGO ZONE
Bendigo
Horsham
STAWELL ZONE
Ararat
GRAMPIANS STAVELY ZONE
GLENELG ZONE
Hamilton
cumulative frequency
1.0
0.5
0
1
2
K_2O wt %
Total Digest

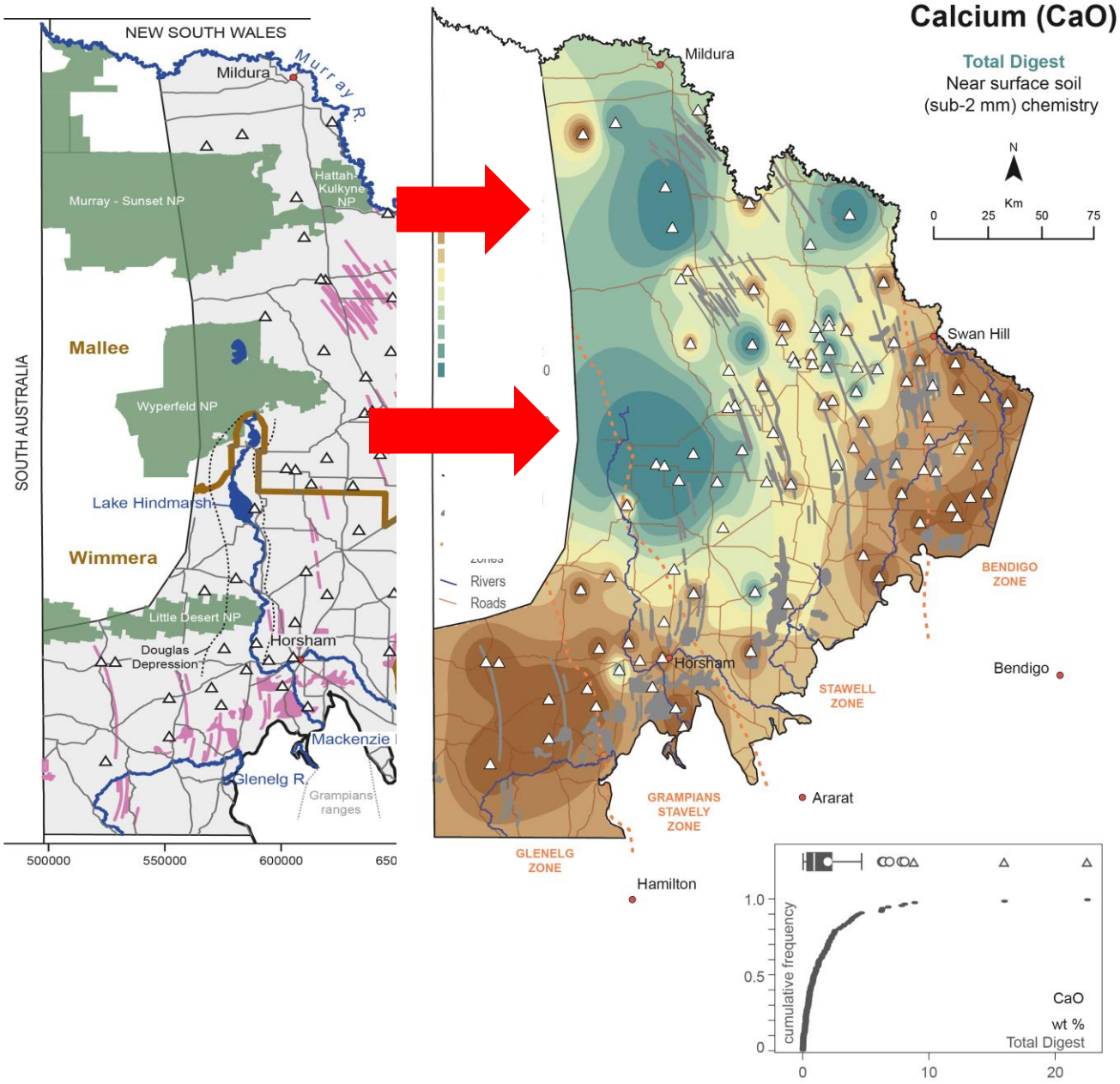

Mallee
Potassium (K_2O)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
K_2O wt %
0.73 - 0.60
0.61 - 0.68
0.69 - 0.72
0.73 - 0.75
0.76 - 0.77
0.78 - 0.83
0.84 - 0.91
0.92 - 1.00
1.01 - 1.13
1.14 - 2.78
Sample sites
0.03 - 2.78
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0
25
50
75
Mildura
Swan Hill
Southern
BENDIGO ZONE
Bendigo
Horsham
STAWELL ZONE
Ararat
GRAMPIANS STAVELY ZONE
Glenelg
GLENELG ZONE
Hamilton
cumulative frequency
1.0
0.5
0
1
2
K_2O
wt %
Total Digest

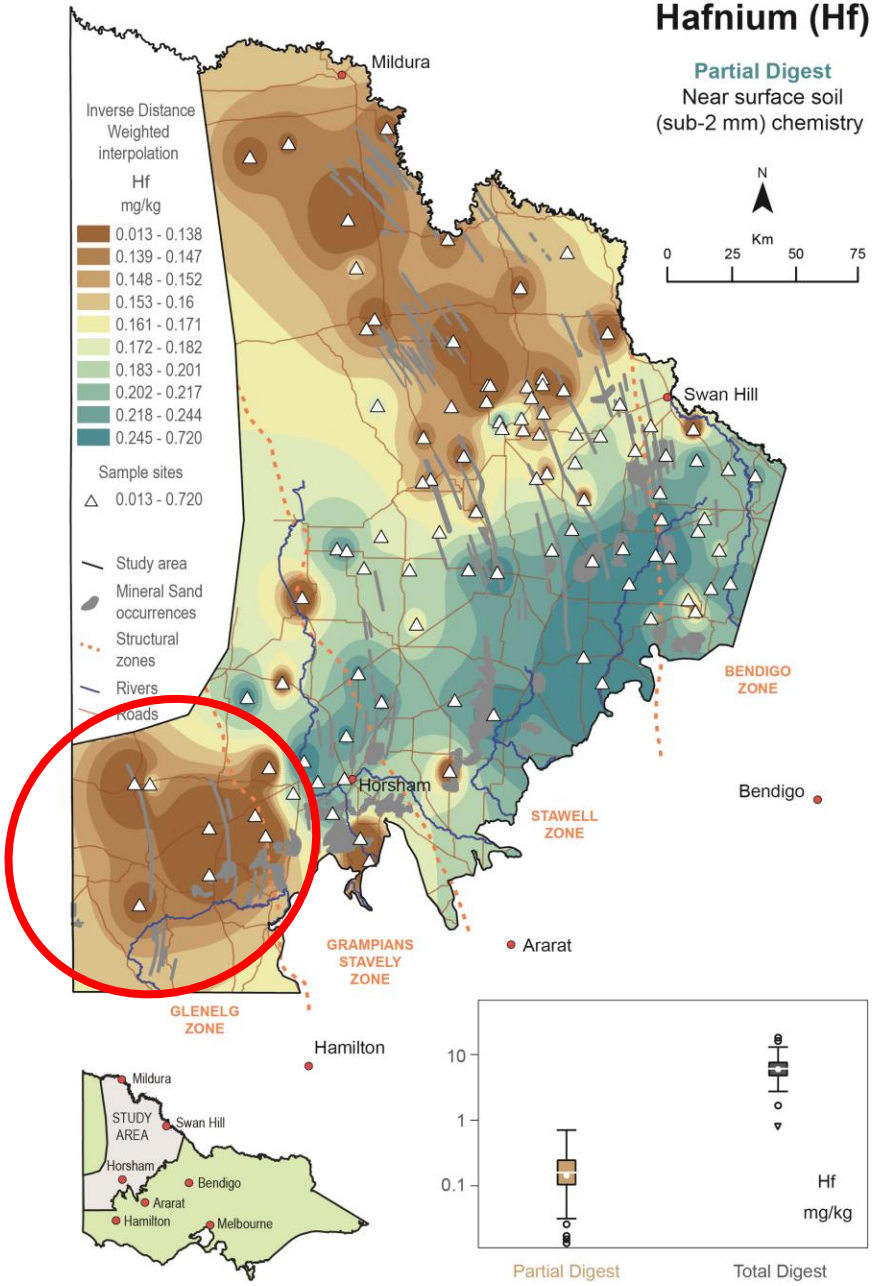


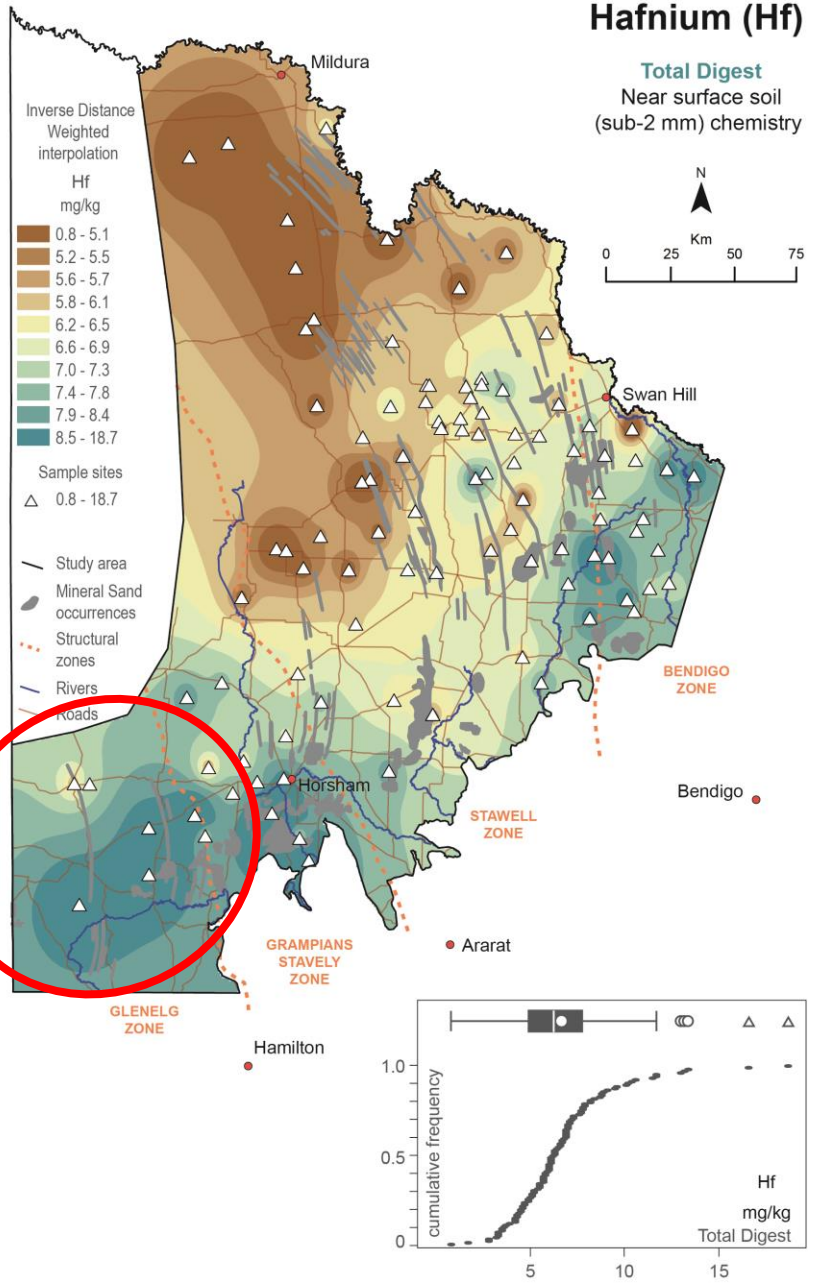
c. 14,000

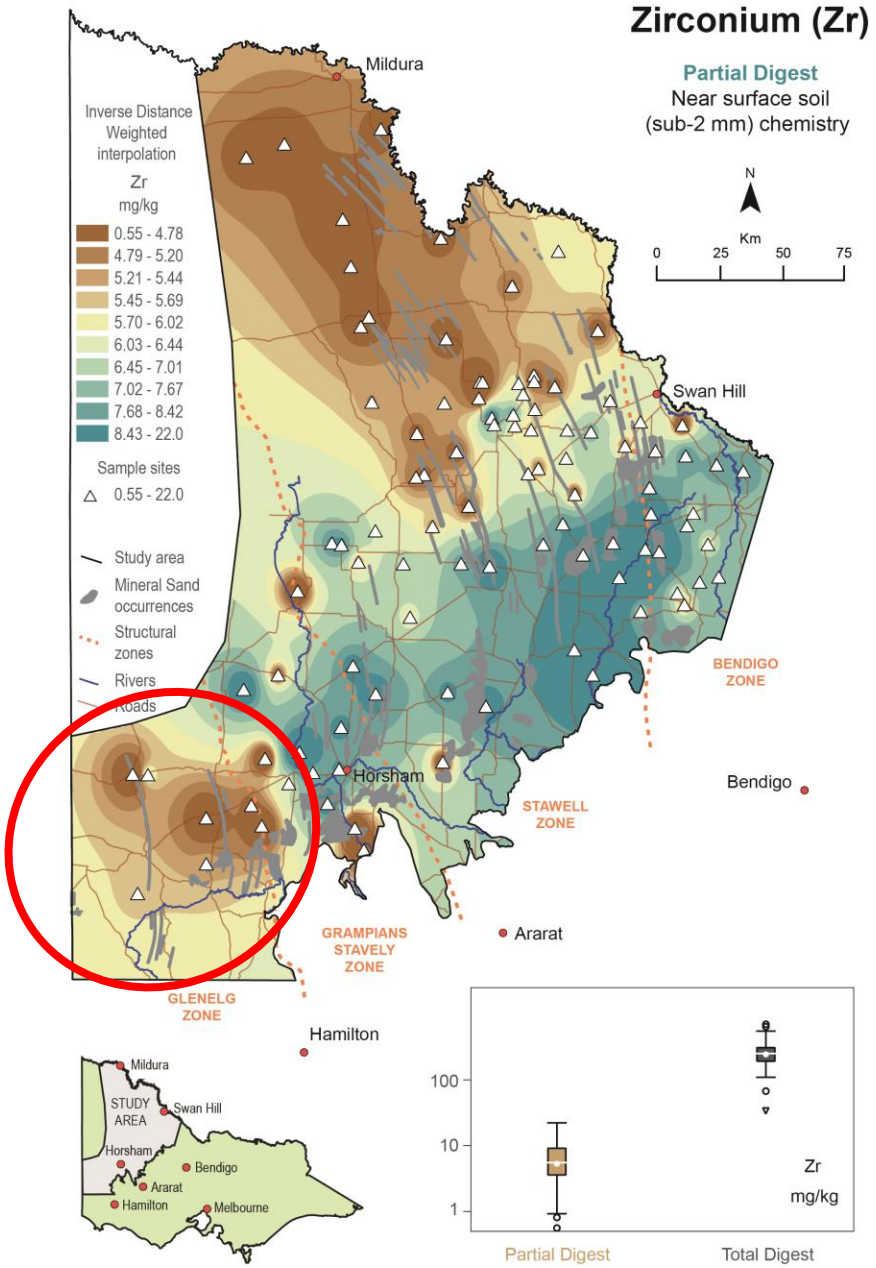
Geology

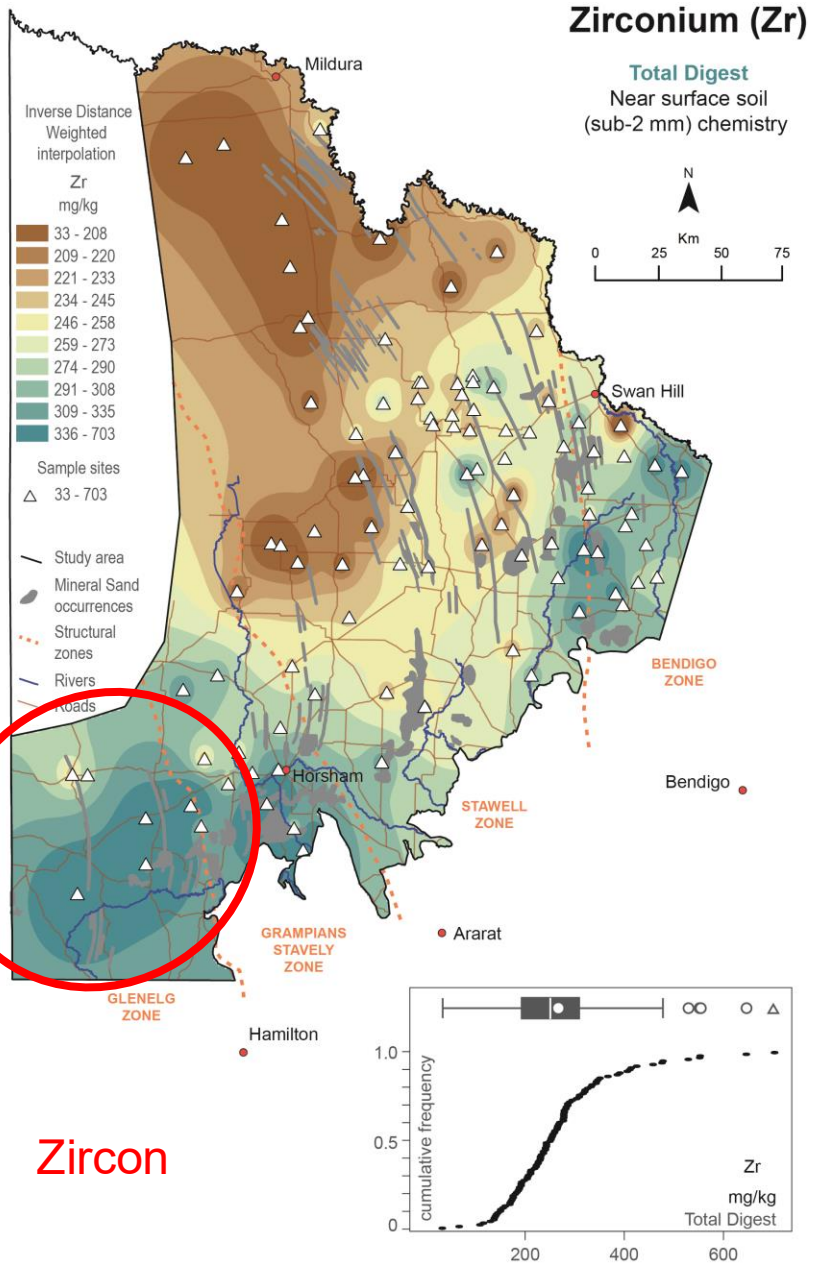
- Calcareous Quaternary dune deposits
- Calcarosol Soil



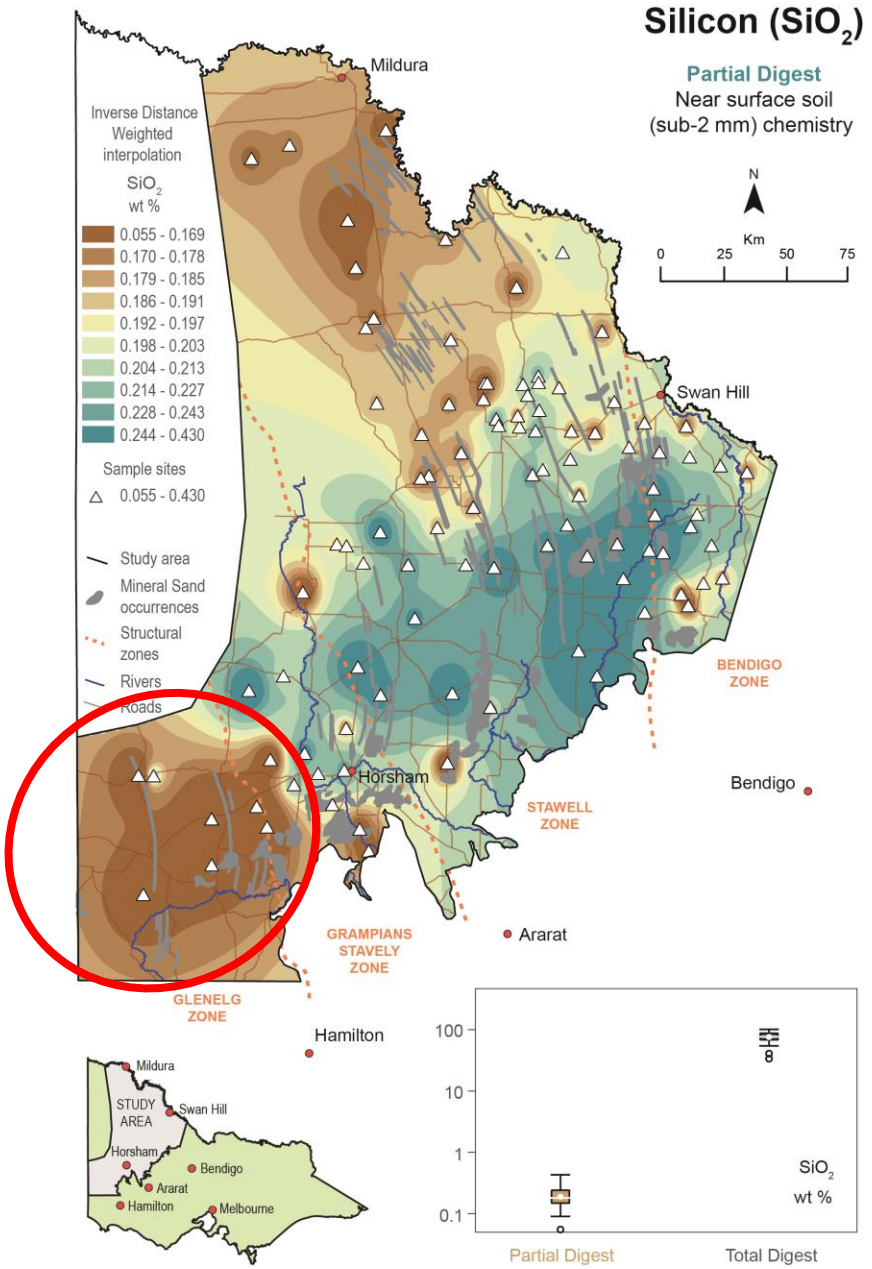

Hafnium (Hf)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
Hf
mg/kg
0.013 - 0.138
0.139 - 0.147
0.148 - 0.152
0.153 - 0.16
0.161 - 0.171
0.172 - 0.182
0.183 - 0.201
0.202 - 0.217
0.218 - 0.244
0.245 - 0.720
Sample sites
0.013 - 0.720
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75
Km
Mildura
Swan Hill
Bendigo
Horsham
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
10
1
0.1
Hf
mg/kg
Partial Digest
Total Digest

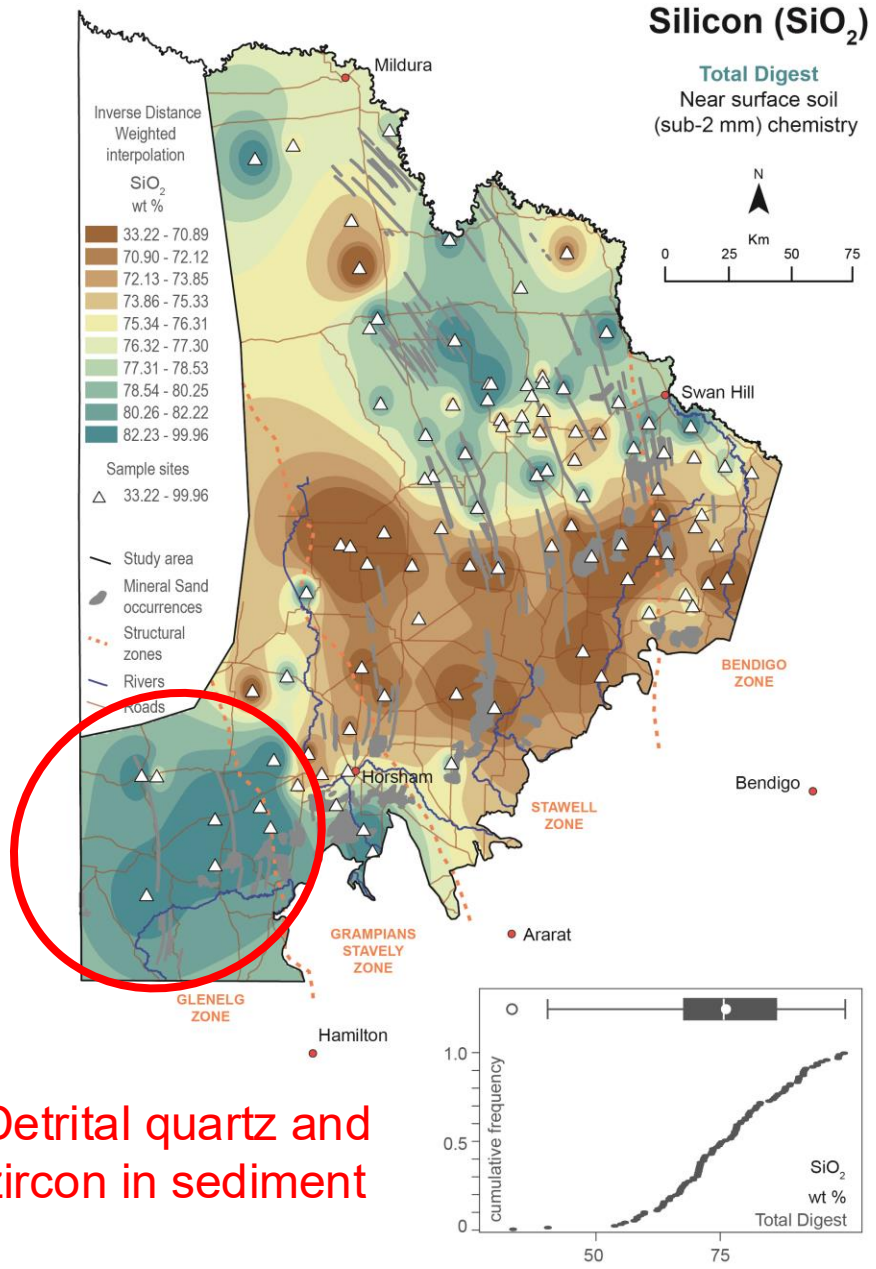

Hafnium (Hf)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
Hf
mg/kg
0.8 - 5.1
5.2 - 5.5
5.6 - 5.7
5.8 - 6.1
6.2 - 6.5
6.6 - 6.9
7.0 - 7.3
7.4 - 7.8
7.9 - 8.4
8.5 - 18.7
Sample sites
0.8 - 18.7
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75
Km
Mildura
Swan Hill
Bendigo
Horsham
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
1.0
0.5
0
cumulative frequency
Hf
mg/kg
Total Digest
5
10
15


Zirconium (Zr)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
Zr
mg/kg
0.55 - 4.78
4.79 - 5.20
5.21 - 5.44
5.45 - 5.69
5.70 - 6.02
6.03 - 6.44
6.45 - 7.01
7.02 - 7.67
7.68 - 8.42
8.43 - 22.0
Sample sites
0.55 - 22.0
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0
25
50
75
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
100
10
1
Zr
mg/kg
Partial Digest
Total Digest

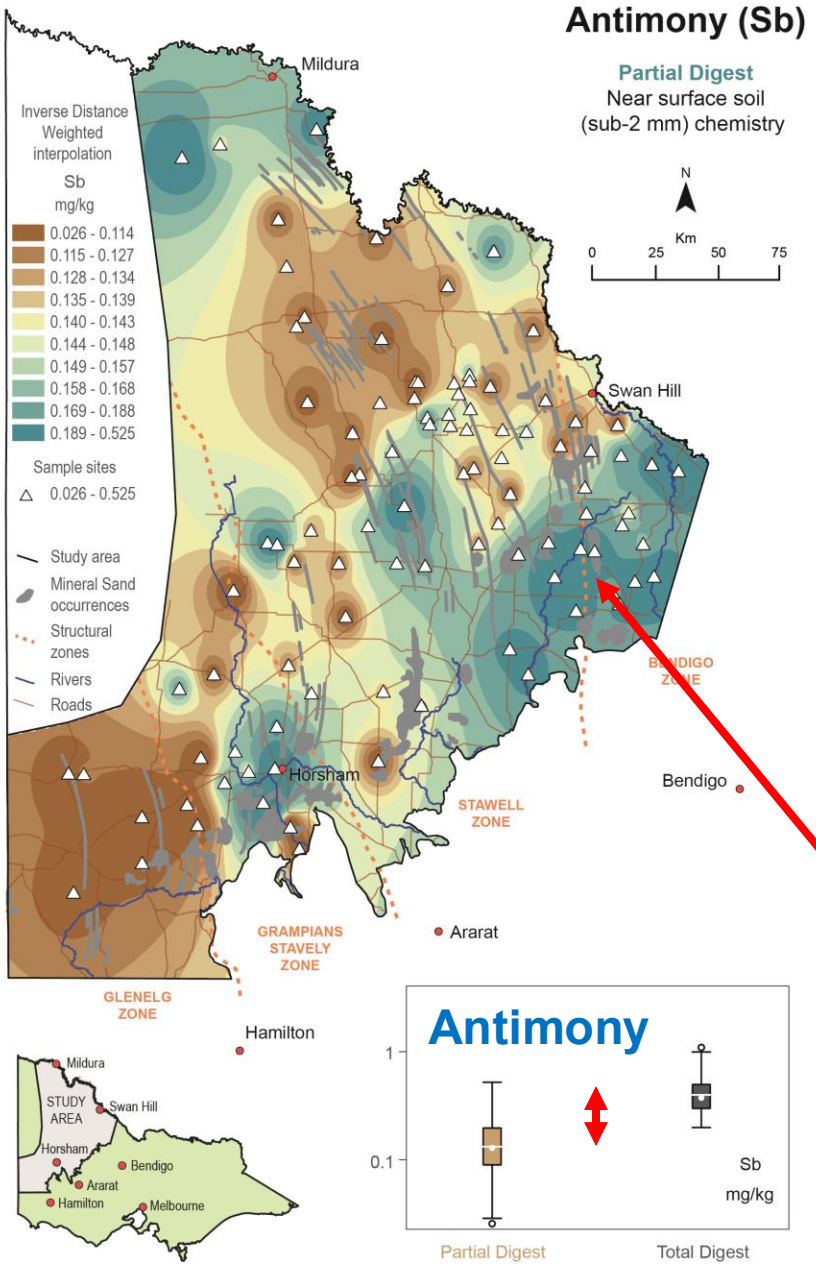

Zirconium (Zr)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
Zr
mg/kg
33 - 208
209 - 220
221 - 233
234 - 245
246 - 258
259 - 273
274 - 290
291 - 308
309 - 335
336 - 703
Sample sites
33 - 703
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0
25
50
75
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
1.0
0.5
0
cumulative frequency
Zr
mg/kg
Total Digest
200
400
600

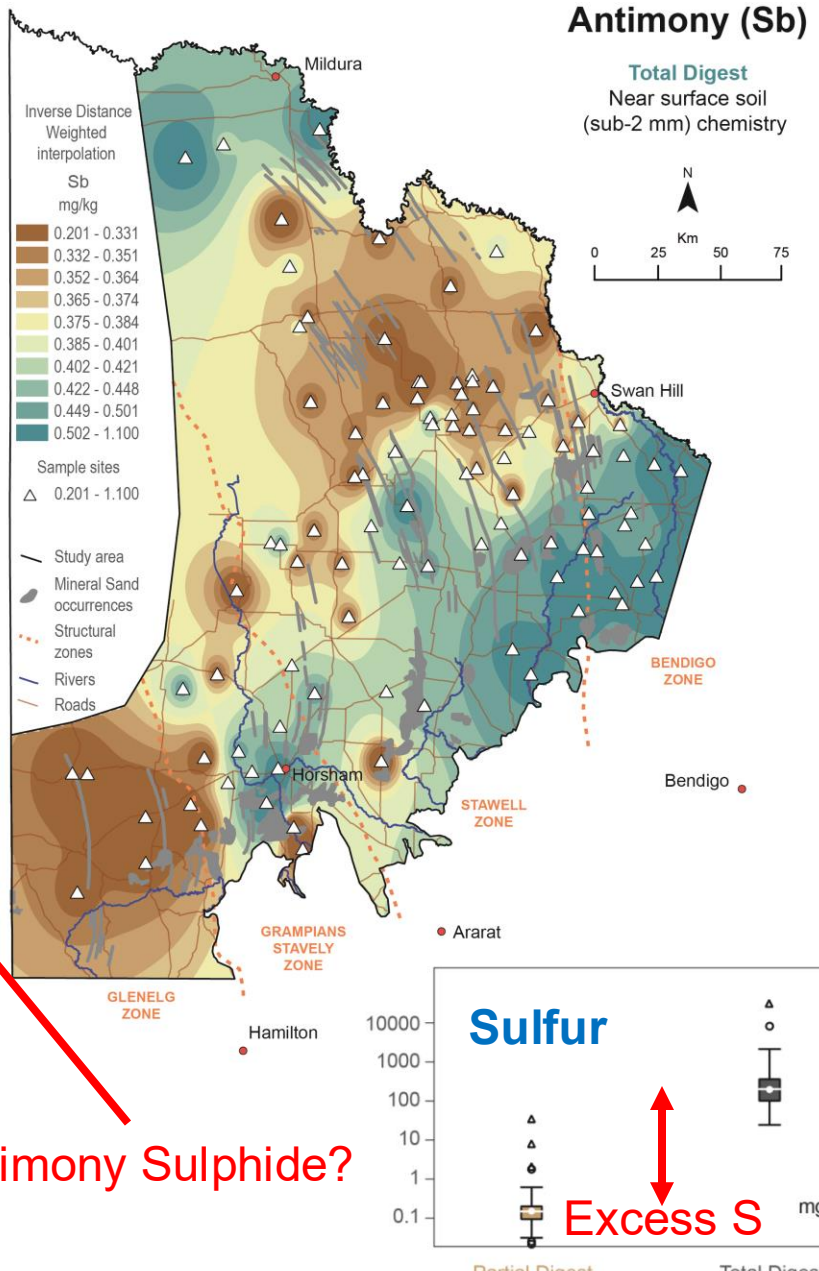
Zircon

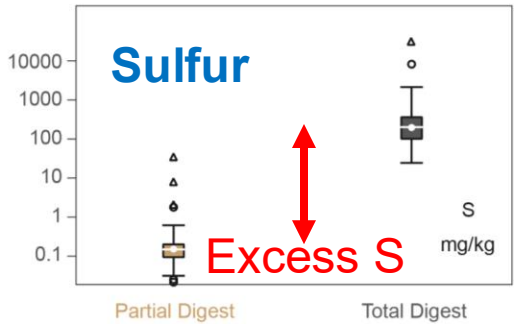




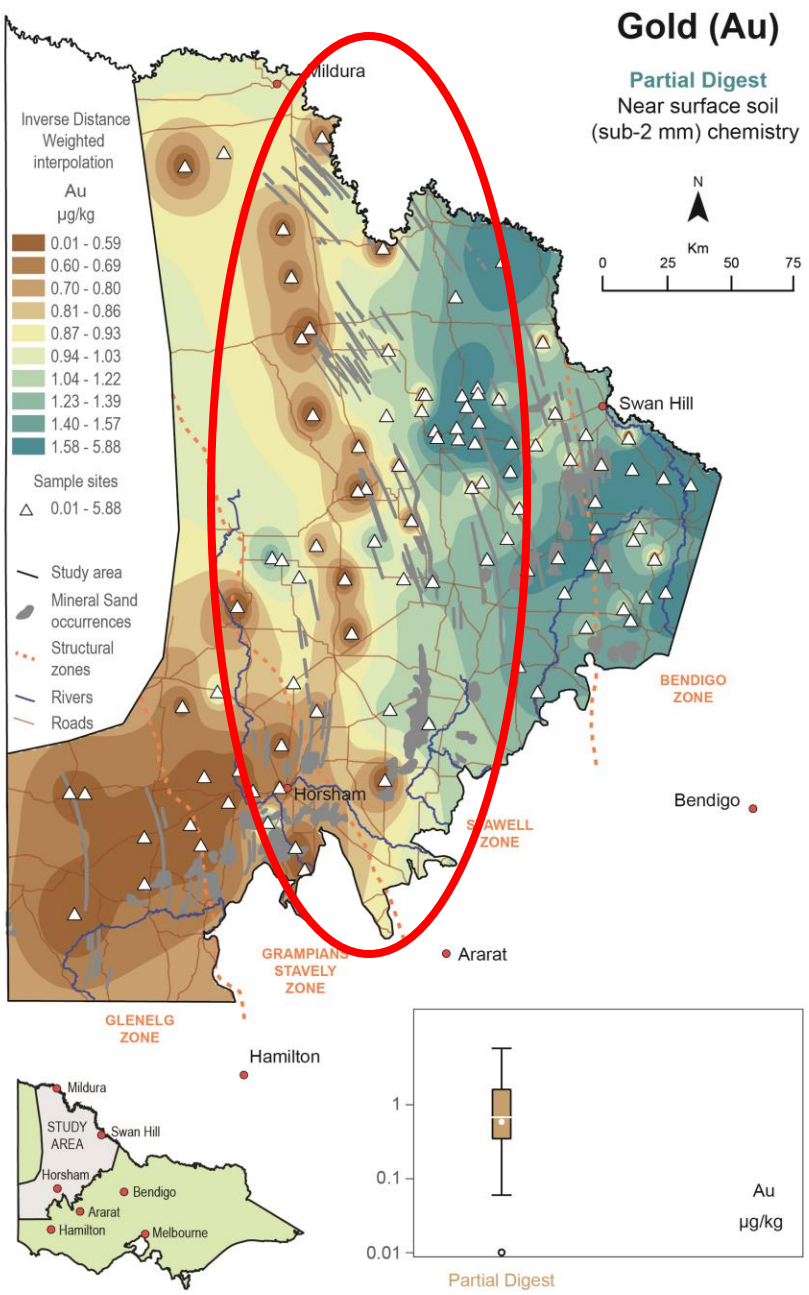
Detrital quartz and zircon in sediment

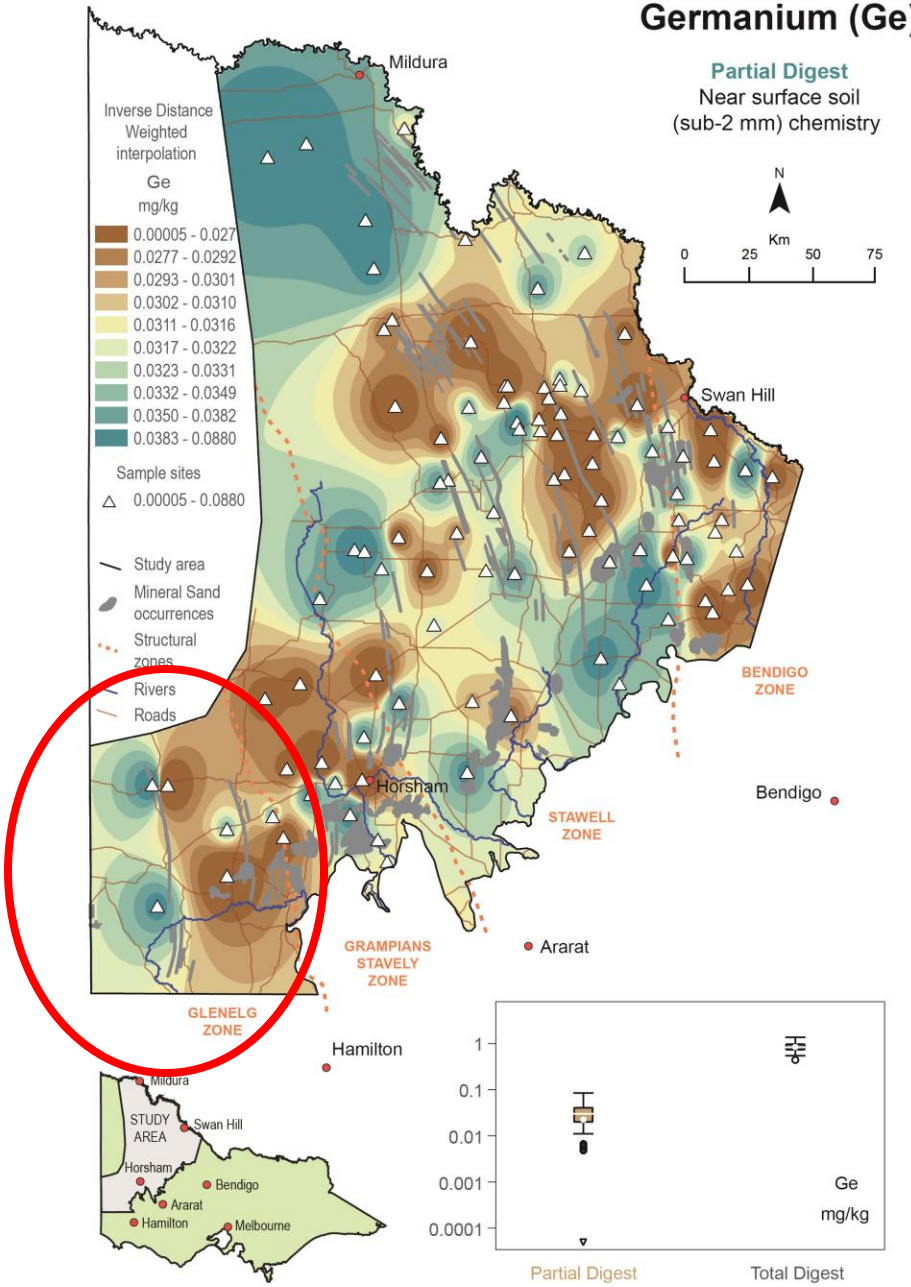


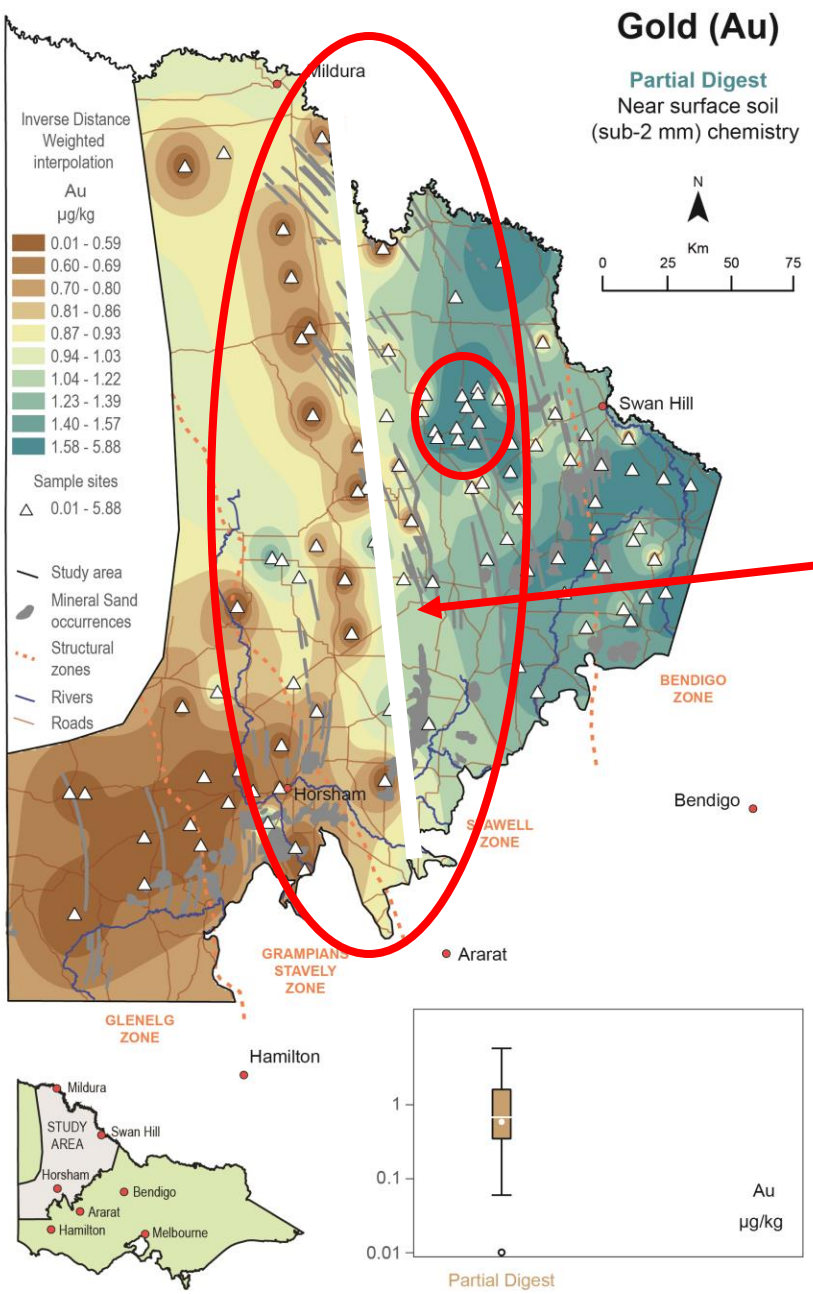




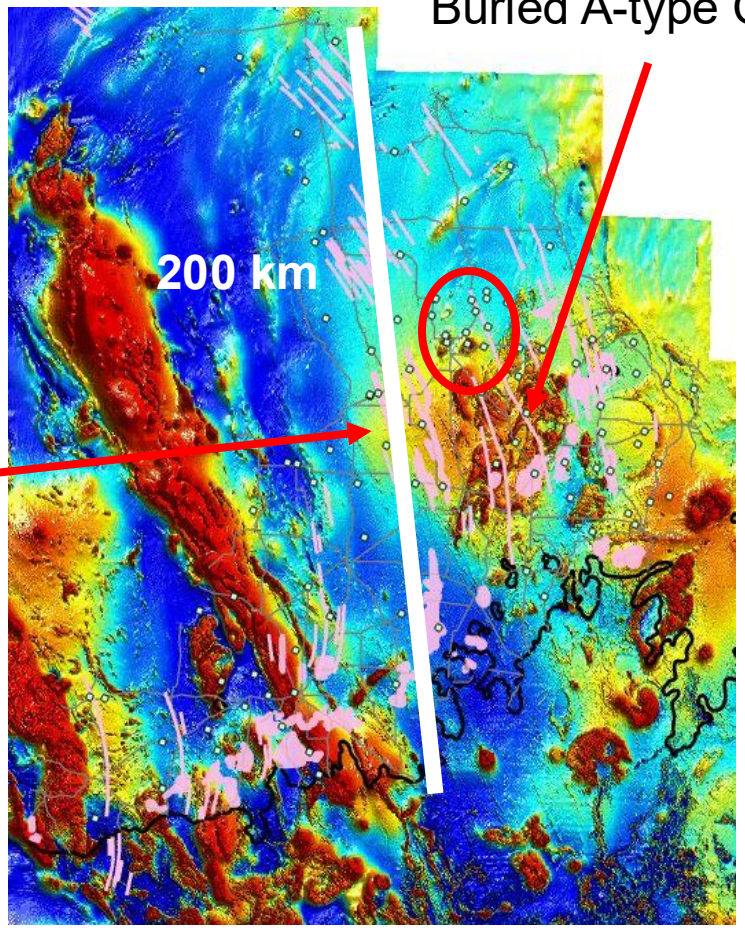
?Antimony Sulphide?


Gold (Au)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
Au
µg/kg
0.01 - 0.59
0.60 - 0.69
0.70 - 0.80
0.81 - 0.86
0.87 - 0.93
0.94 - 1.03
1.04 - 1.22
1.23 - 1.39
1.40 - 1.57
1.58 - 5.88
Sample sites
0.01 - 5.88
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75
Km
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
1
0.1
0.01
Au
µg/kg
Partial Digest


Germanium (Ge)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
Ge
mg/kg
0.00005 - 0.027
0.0277 - 0.0292
0.0293 - 0.0301
0.0302 - 0.0310
0.0311 - 0.0316
0.0317 - 0.0322
0.0323 - 0.0331
0.0332 - 0.0349
0.0350 - 0.0382
0.0383 - 0.0880
Sample sites
0.00005 - 0.0880
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75
Km
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
1
0.1
0.01
0.001
0.0001
Ge
mg/kg
Partial Digest
Total Digest

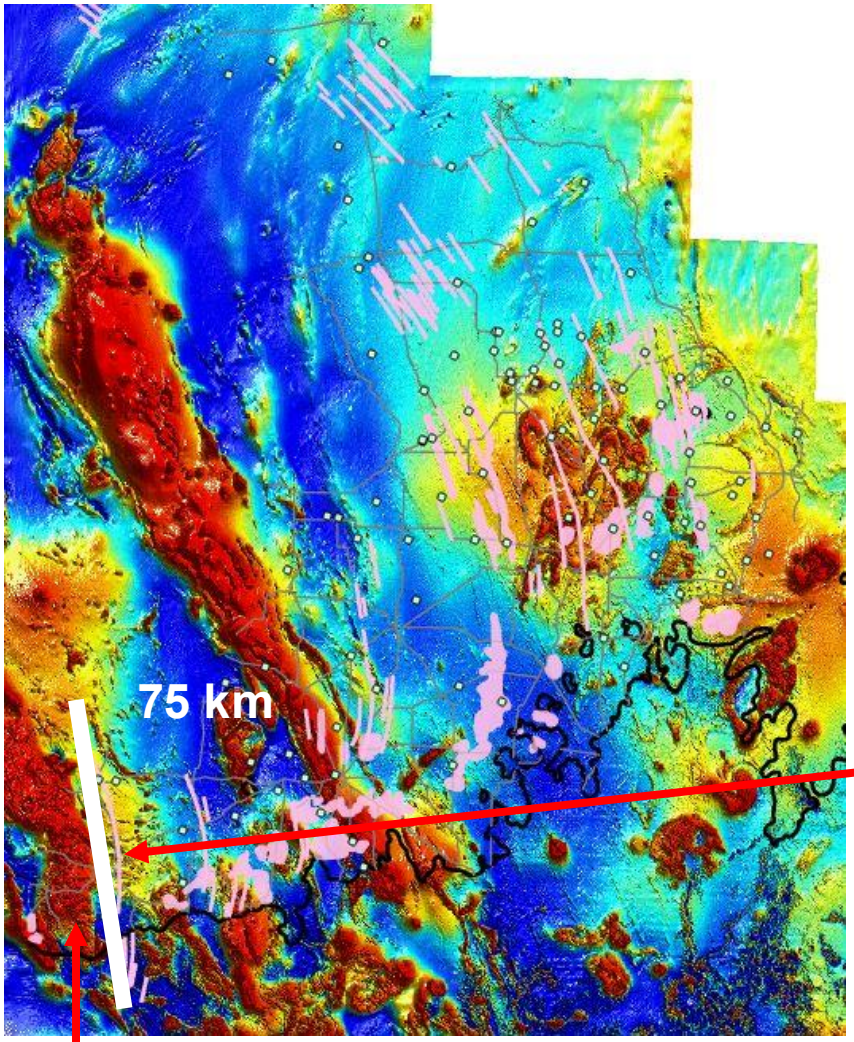


Buried A-type Granite

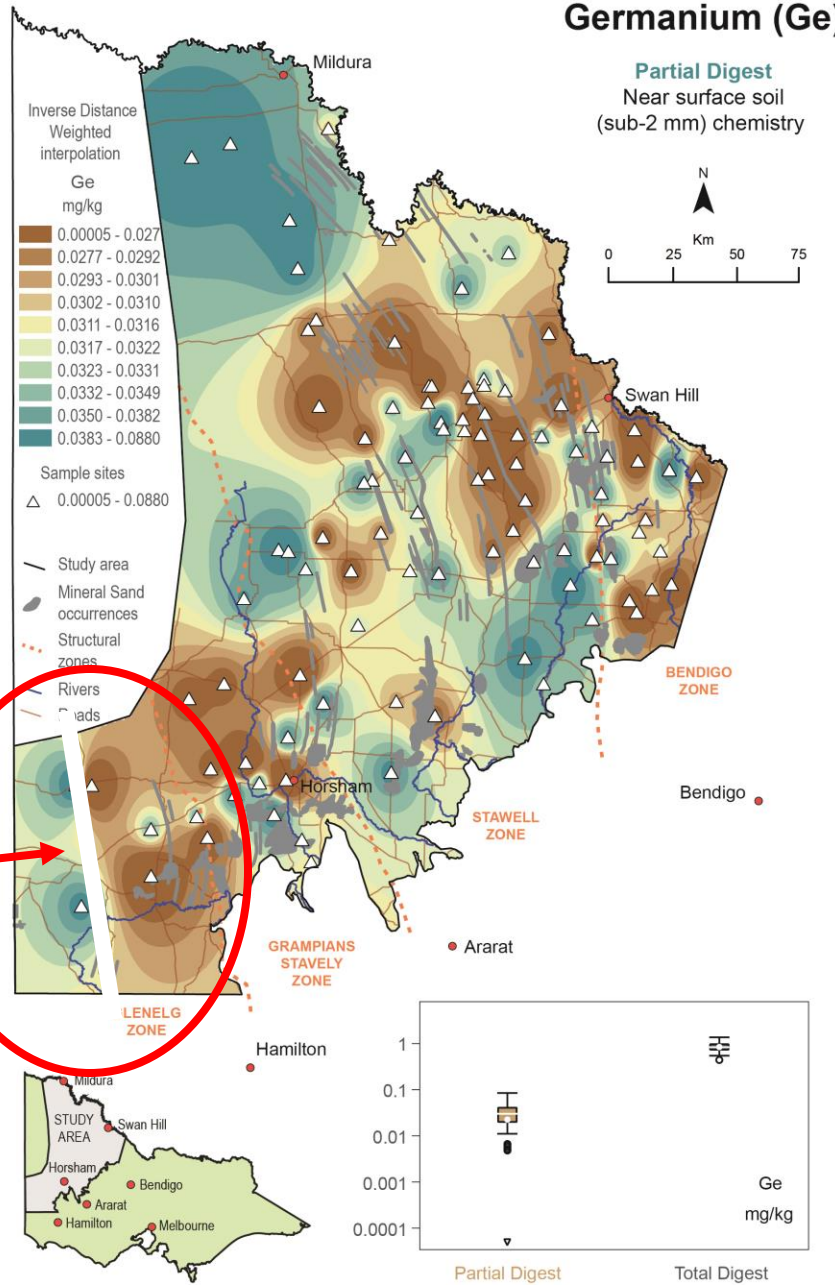


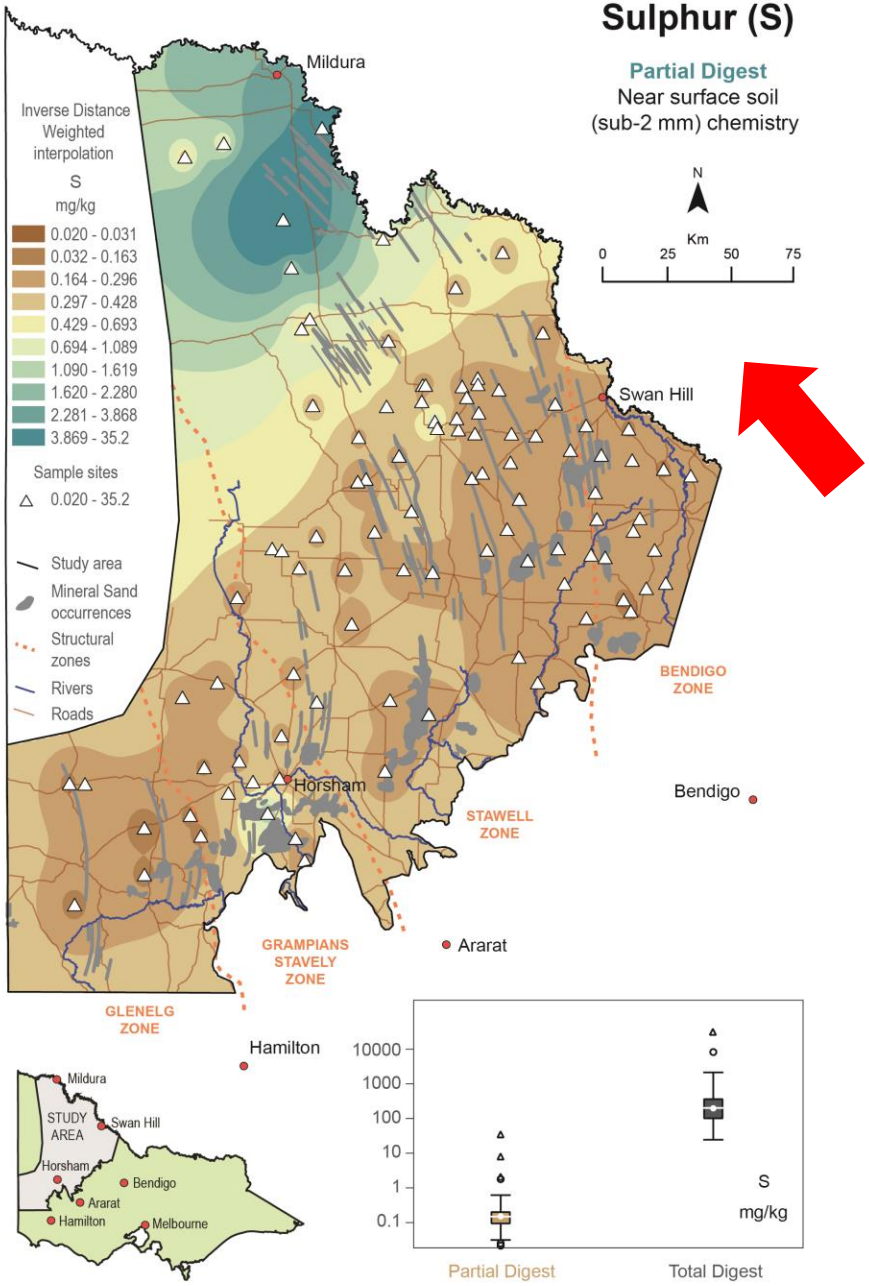
Mag RTP

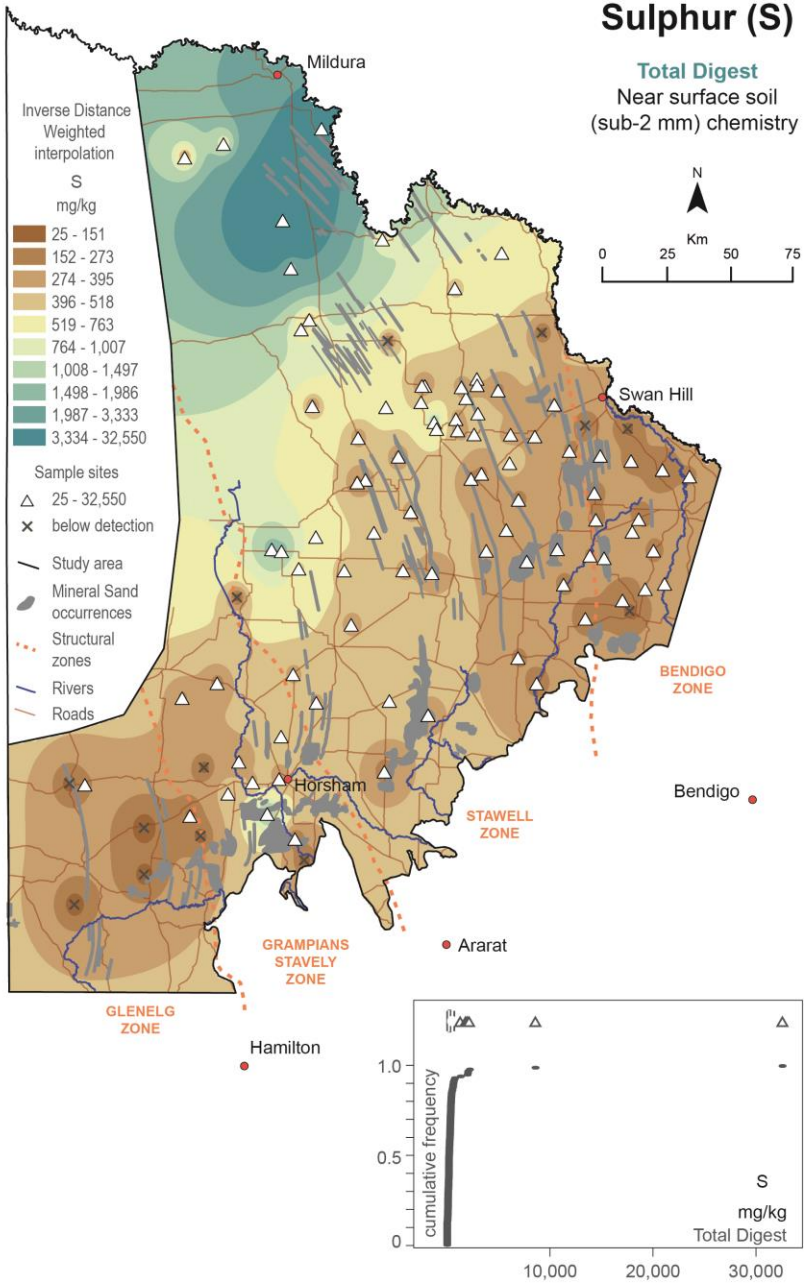
Mag RTP

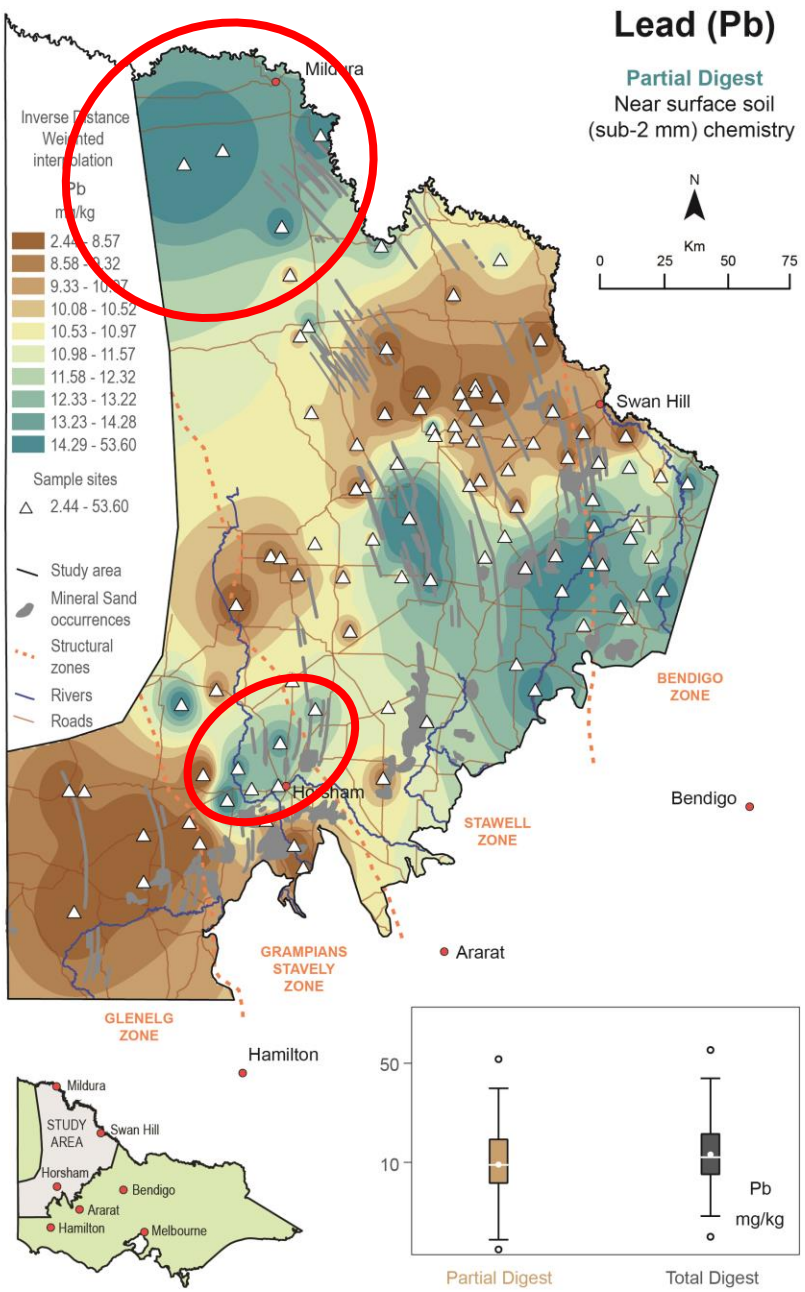


Buried A-type Granite



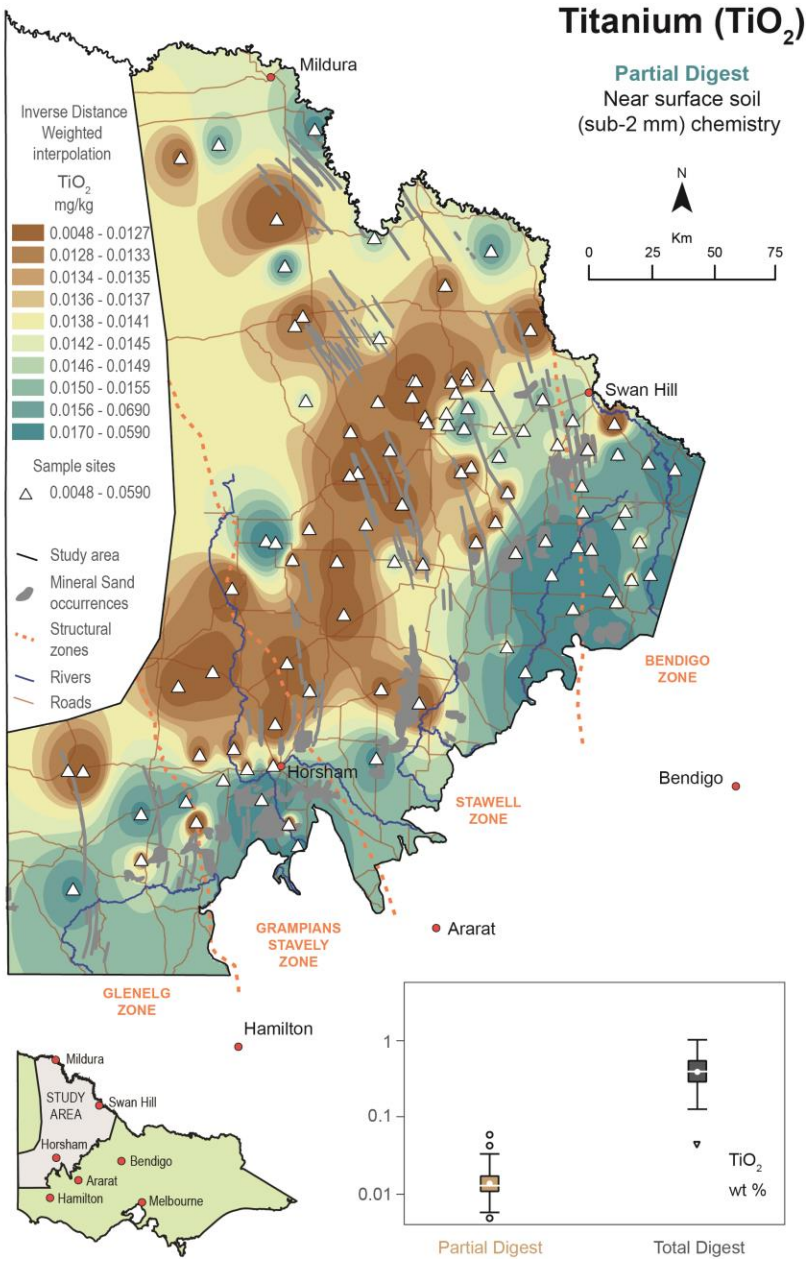

Sulphur (S)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Mildura
Swan Hill
Bendigo
Horsham
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
Inverse Distance Weighted interpolation
S
mg/kg
0.020 - 0.031
0.032 - 0.163
0.164 - 0.296
0.297 - 0.428
0.429 - 0.693
0.694 - 1.089
1.090 - 1.619
1.620 - 2.280
2.281 - 3.868
3.869 - 35.2
Sample sites
0.020 - 35.2
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0 25 50 75
STUDY AREA
10000
1000
100
10
1
0.1
S
mg/kg
Partial Digest
Total Digest

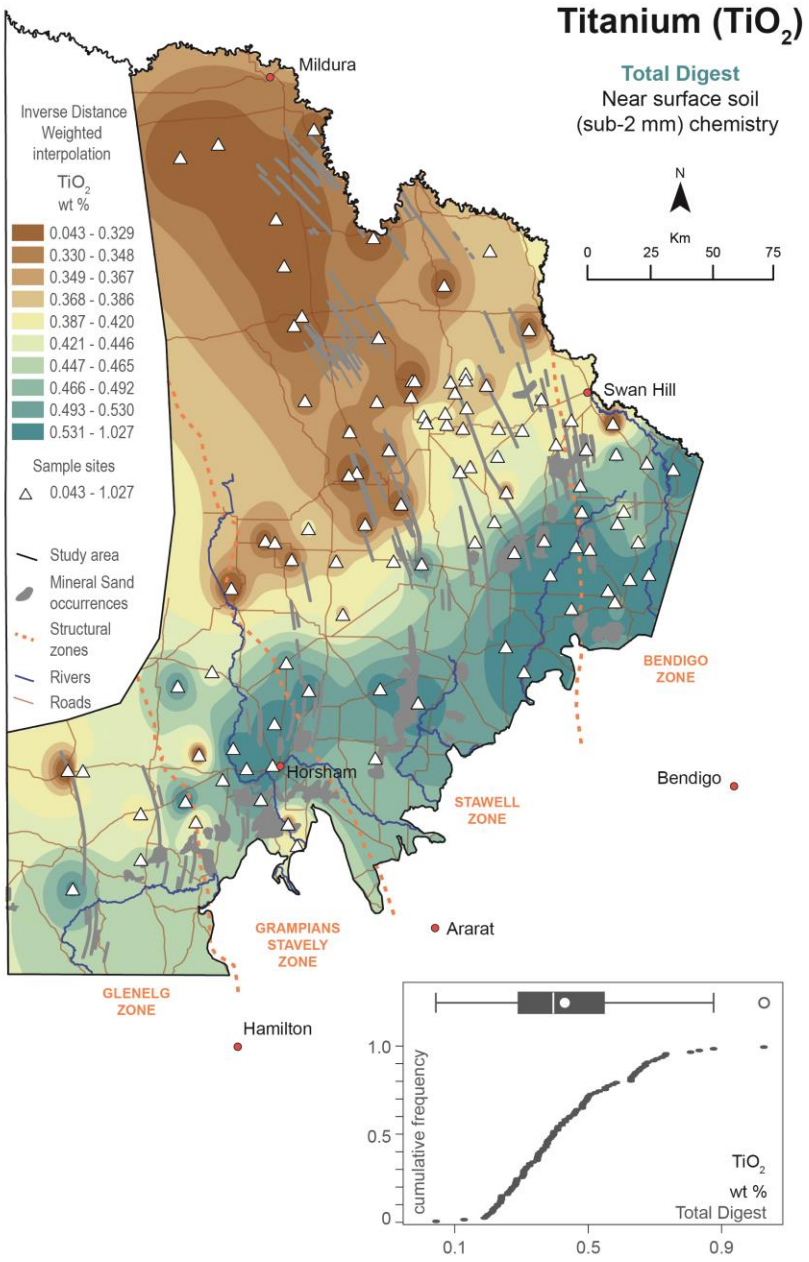

Sulphur (S)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Mildura
Swan Hill
Bendigo
Horsham
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
Inverse Distance Weighted interpolation
S
mg/kg
25 - 151
152 - 273
274 - 395
396 - 518
519 - 763
764 - 1,007
1,008 - 1,497
1,498 - 1,986
1,987 - 3,333
3,334 - 32,550
Sample sites
25 - 32,550
below detection
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0 25 50 75
cumulative frequency
1.0
0.5
0
S
mg/kg
Total Digest
10,000
20,000
30,000

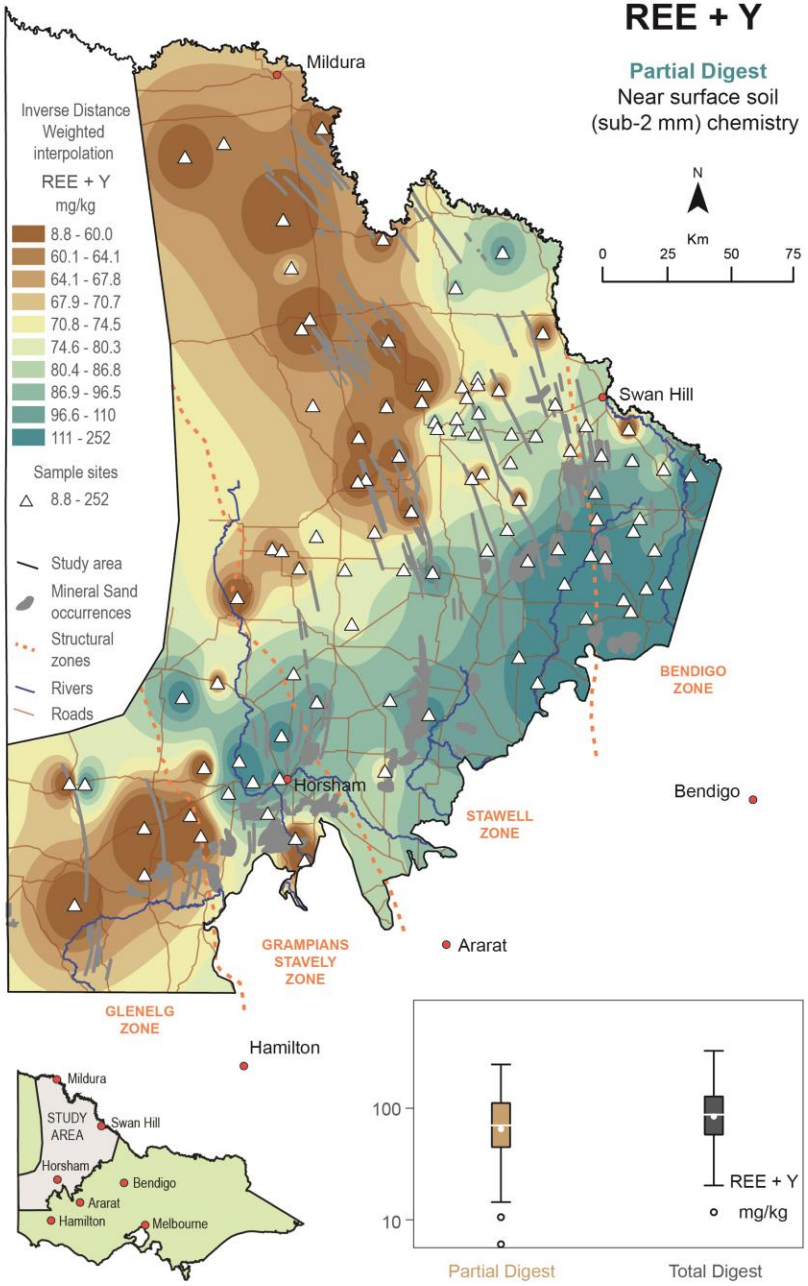


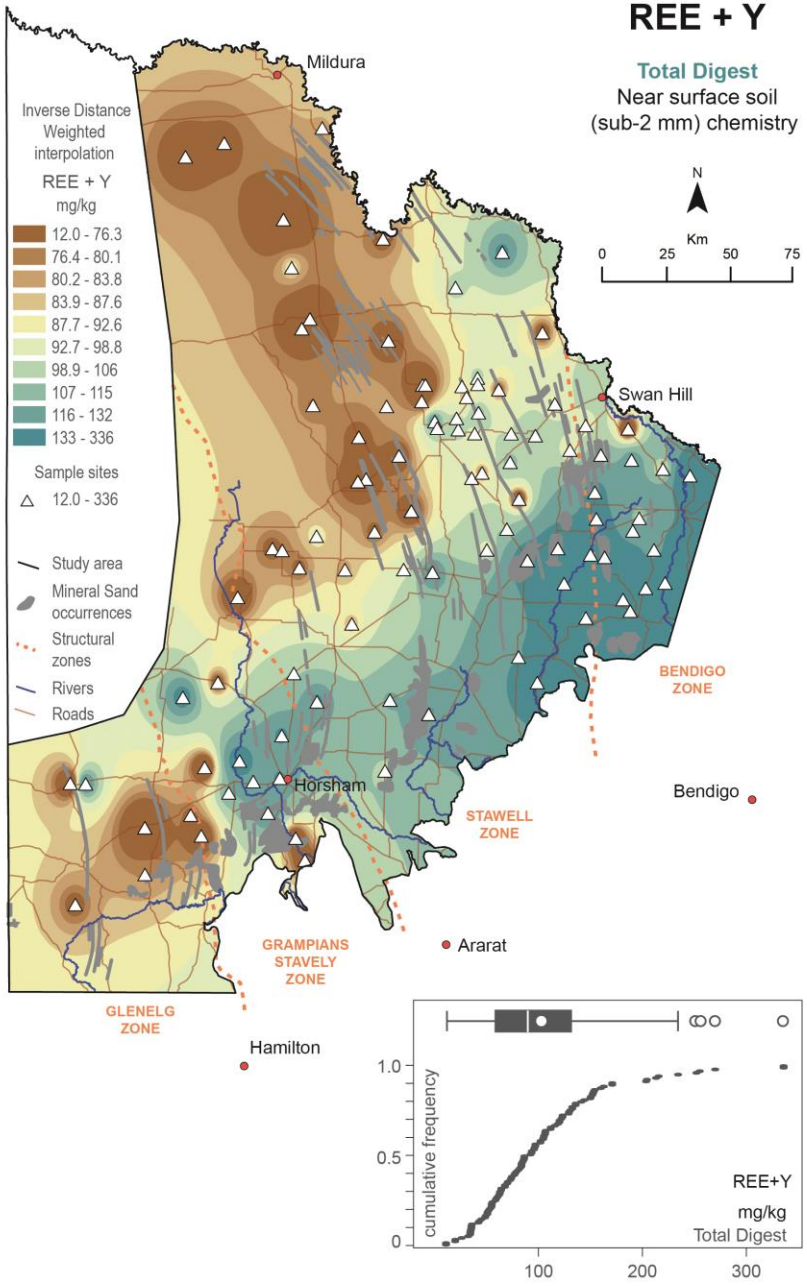
Land Use Factors

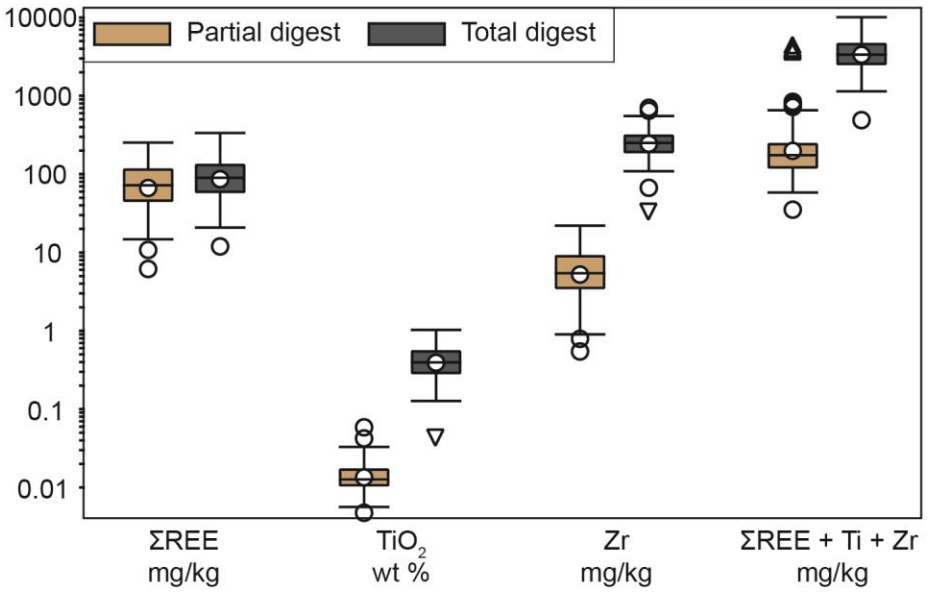
- Fertiliser application ± urbanisation


Titanium (TiO_2)
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
TiO_2 mg/kg
0.0048 - 0.0127
0.0128 - 0.0133
0.0134 - 0.0135
0.0136 - 0.0137
0.0138 - 0.0141
0.0142 - 0.0145
0.0146 - 0.0149
0.0150 - 0.0155
0.0156 - 0.0690
0.0170 - 0.0590
Sample sites
0.0048 - 0.0590
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75 Km
Mildura
Swan Hill
Bendigo
Horsham
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
1
0.1
0.01
TiO_2 wt %
Partial Digest
Total Digest

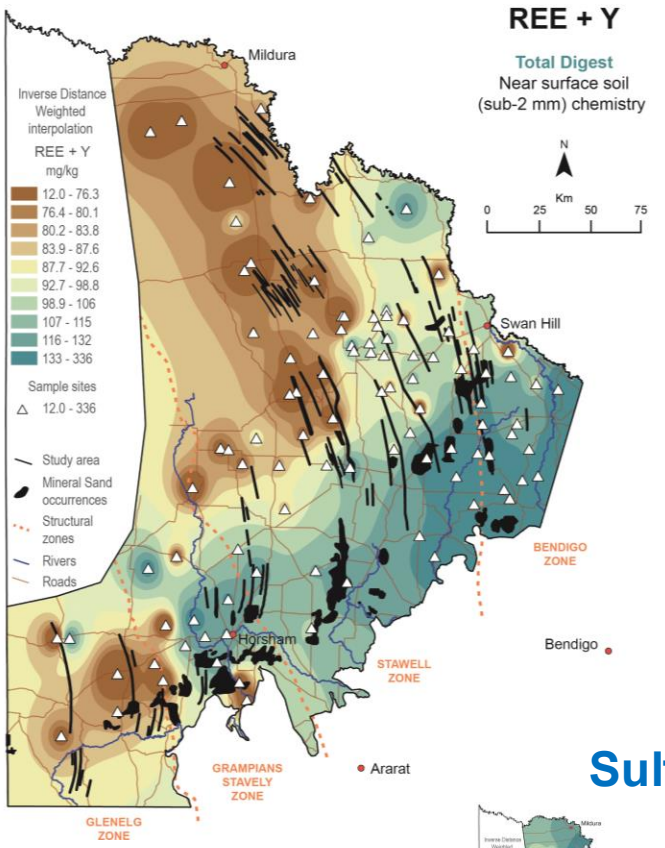

Titanium (TiO_2)
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
TiO_2 wt %
0.043 - 0.329
0.330 - 0.348
0.349 - 0.367
0.368 - 0.386
0.387 - 0.420
0.421 - 0.446
0.447 - 0.465
0.466 - 0.492
0.493 - 0.530
0.531 - 1.027
Sample sites
0.043 - 1.027
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
0 25 50 75 Km
Mildura
Swan Hill
Bendigo
Horsham
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
cumulative frequency
1.0
0.5
0
0.1
0.5
0.9
TiO_2 wt % Total Digest


REE + Y
Partial Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
REE + Y
mg/kg
8.8 - 60.0
60.1 - 64.1
64.1 - 67.8
67.9 - 70.7
70.8 - 74.5
74.6 - 80.3
80.4 - 86.8
86.9 - 96.5
96.6 - 110
111 - 252
Sample sites
8.8 - 252
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0 25 50 75
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
STUDY AREA
Melbourne
100
10
REE + Y
mg/kg
Partial Digest
Total Digest

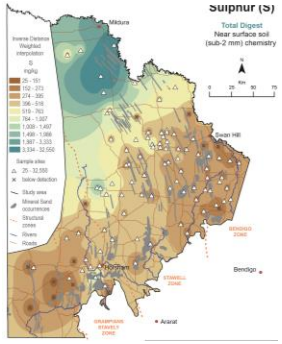

REE + Y
Total Digest
Near surface soil
(sub-2 mm) chemistry
Inverse Distance Weighted interpolation
REE + Y
mg/kg
12.0 - 76.3
76.4 - 80.1
80.2 - 83.8
83.9 - 87.6
87.7 - 92.6
92.7 - 98.8
98.9 - 106
107 - 115
116 - 132
133 - 336
Sample sites
12.0 - 336
Study area
Mineral Sand occurrences
Structural zones
Rivers
Roads
N
Km
0 25 50 75
Mildura
Swan Hill
Horsham
Bendigo
Ararat
Hamilton
BENDIGO ZONE
STAWELL ZONE
GRAMPIANS STAVELY ZONE
GLENELG ZONE
cumulative frequency
1.0
0.5
0
100
200
300
REE+Y
mg/kg
Total Digest



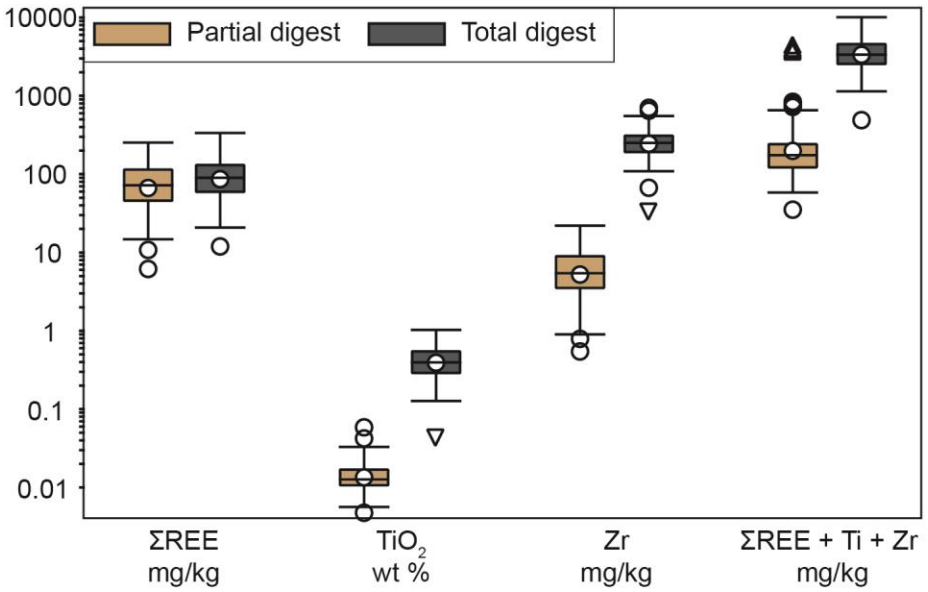
rutile, anatase, ilmenite, zircon, monazite and xenotime



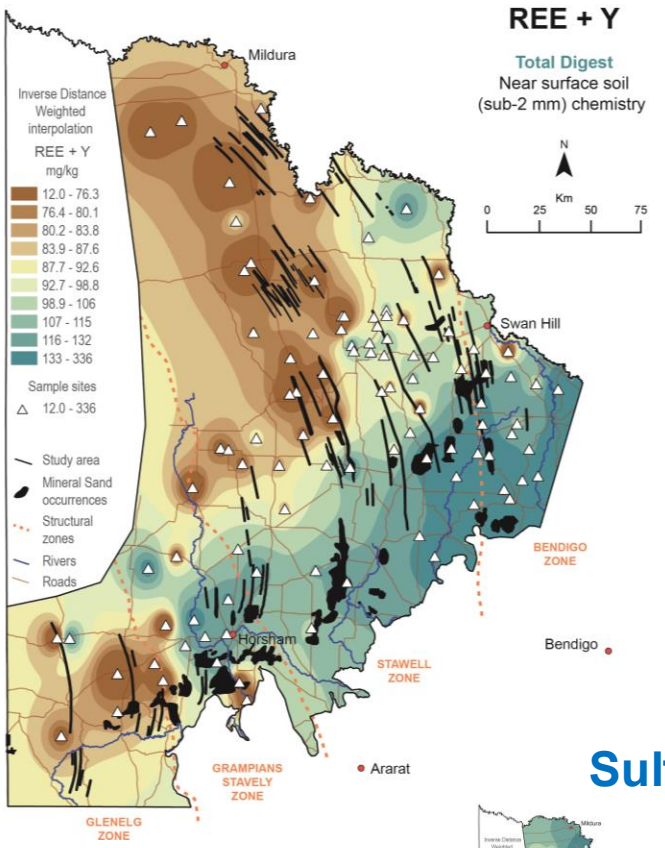
Sulfur



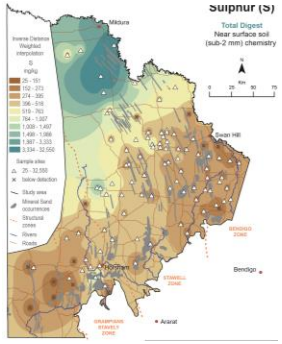
- Local Geology
  - Weathering of parilla-sand derived heavy mineral occurrences
- Anthropogenic
  - Fertilizer addition (e.g. Bispo et al. 2021, Enviro. Pol. V289)
- Distal Geology
  - River catchment geology



rutile, anatase, ilmenite, zircon, monazite and xenotime

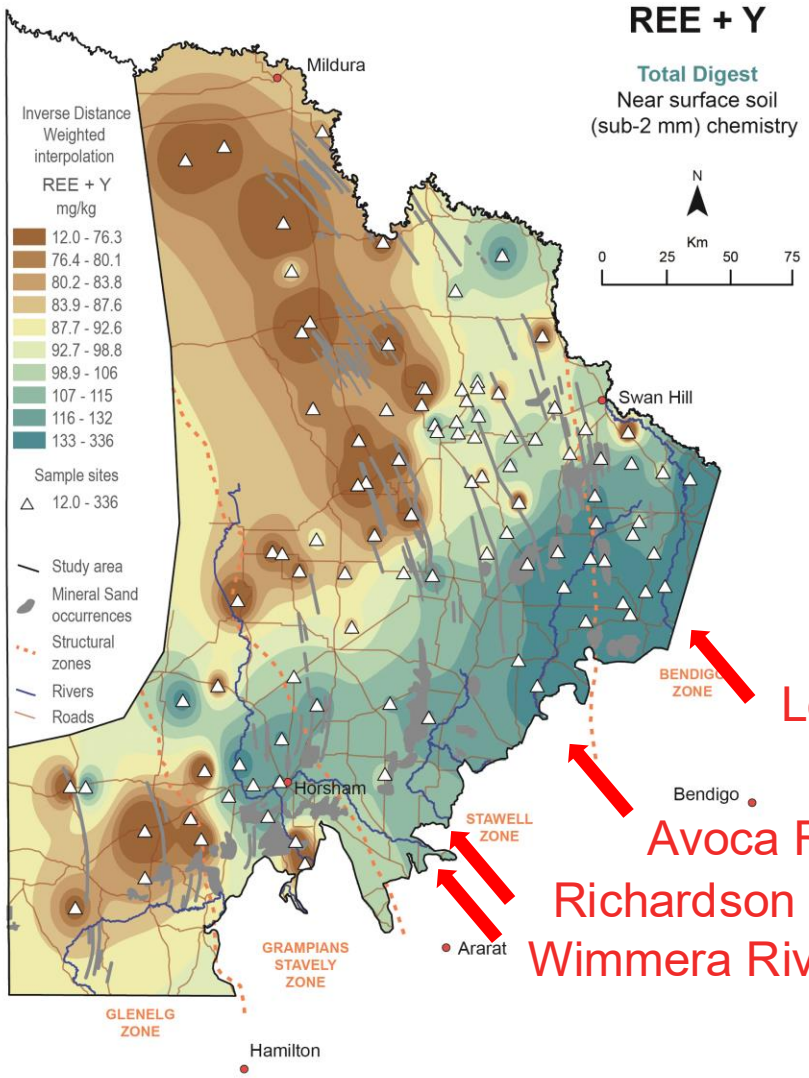


Sulfur



- Local Geology
  - Weathering of parilla-sand derived heavy mineral occurrences
- Anthropogenic
  - Fertilizer addition (e.g. Bispo et al. 2021, Enviro. Pol. V289)
- Distal Geology
  - River catchment geology

- Alluvium-colluvium signal dominates southern study area
- Other analytical approaches required for critical mineral exploration
- Normalisation factor varies geographically



River Flow Direction

Loddon River

Avoca River

Richardson River

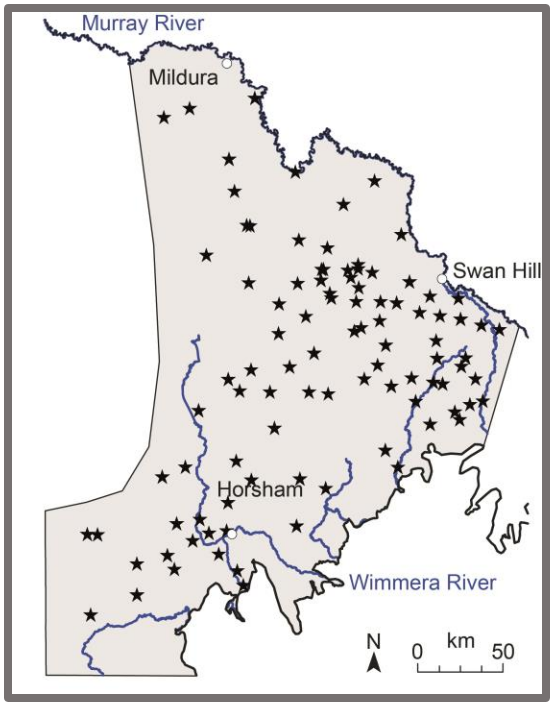
Wimmera River

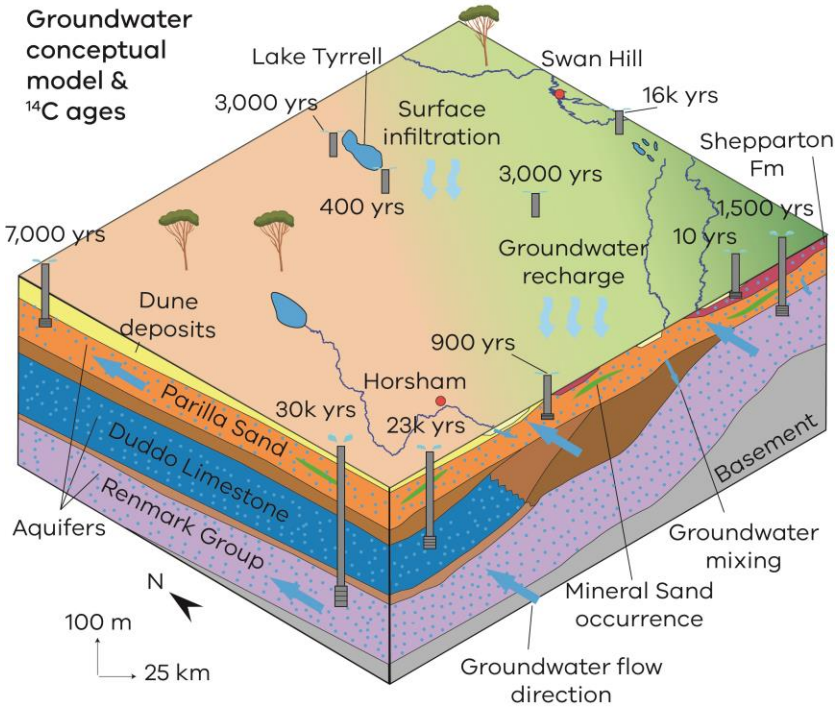
BASEMENT

Glenelg Zone | Grampians Stavely Zone | Stawell Zone | Bendigo Zone

Groundwater

- 163 groundwater samples were collected from the state bore network across the study area
- Major, minor, trace elements analysed, including for Ti, Zr, REE

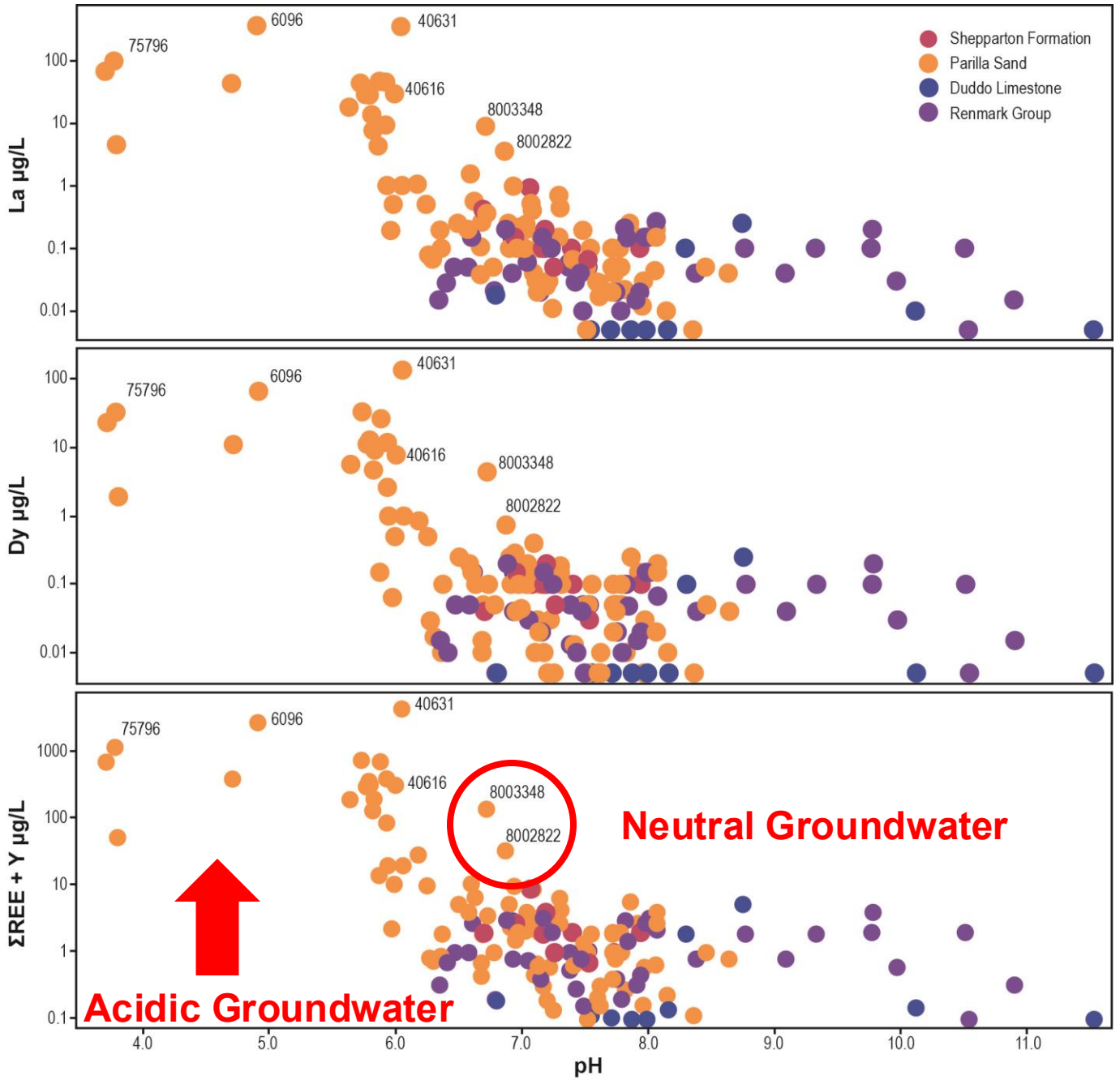




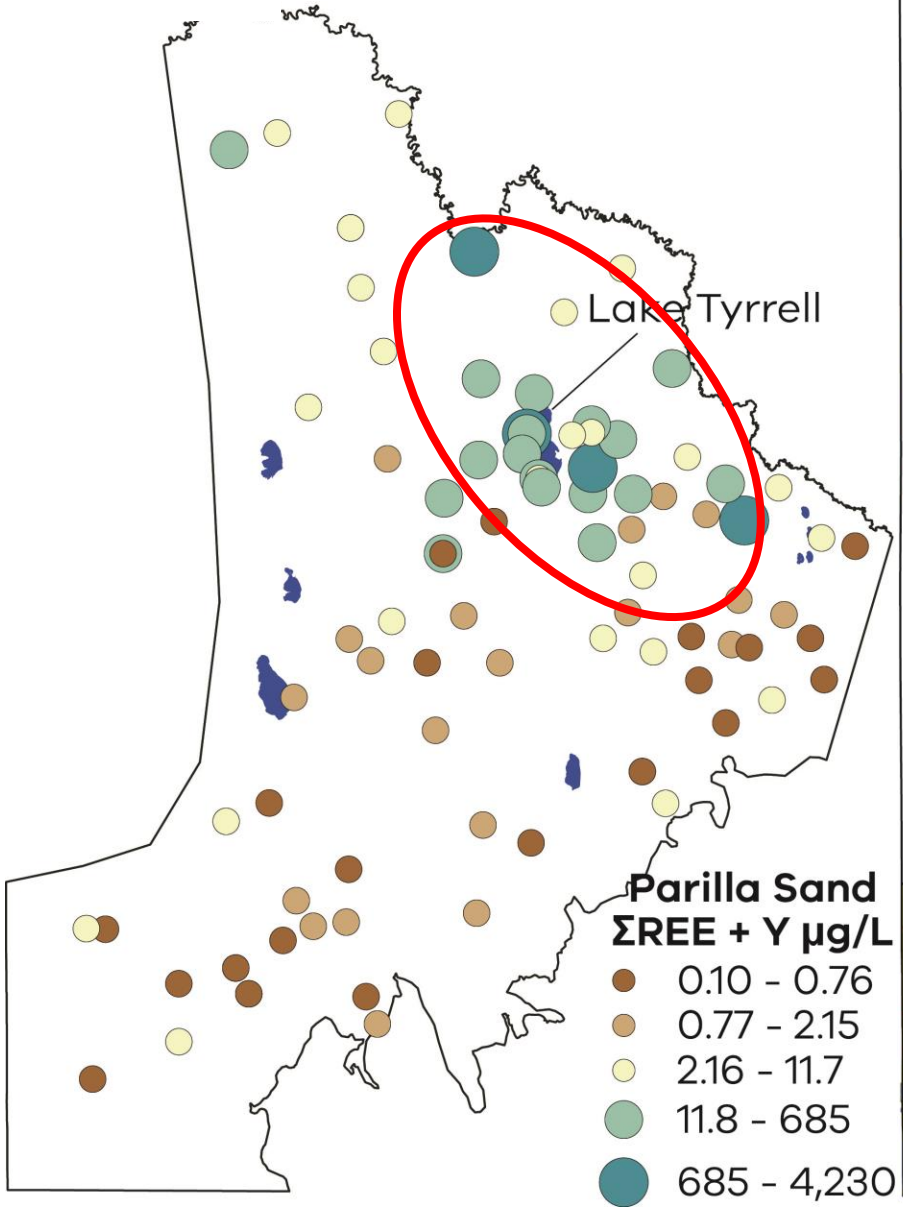
La

Dy

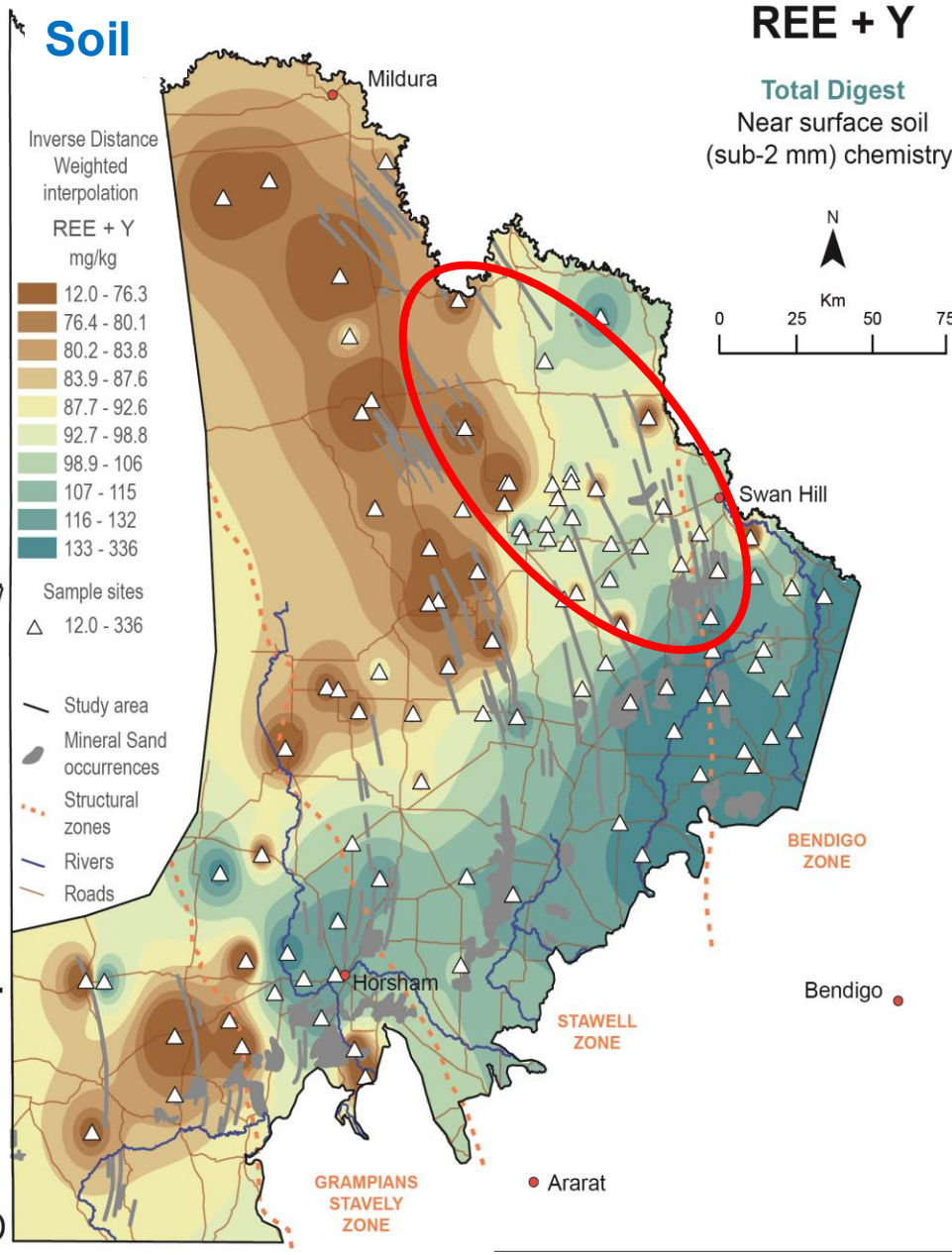
Total REE



Groundwater



Soil



Bringing it all together

- A snapshot of soil geochemistry of northwest Victoria in 2025
- Soil parent material = fluvially derived in the south or calcareous dune deposits in the north
- Soil mineralogy assessed by Hylogger and differences between partial digest and total digest
- Factors influencing soil geochemistry
  - Geologic (mineralogy)
  - Anthropic (fertiliser, urban centres)
  - Physiographic (rivers)
- Soil REE, Ti and Zr anomalies primarily reflect changes in river catchment geology, c.f. weathering from underlying heavy mineral occurrences
- Groundwater REE anomalies associated with acidic water and the link to mineral sand occurrences is being investigated

Aim 1: The geochemistry in soil baseline data, in conjunction with the other sample mediums, can be used as a basis for future monitoring and evaluation
Aim 2: Other approaches required for soil critical mineral exploration but groundwater may be of use

Future Other Victorian regions, new techniques, integration with NGSA, refine survey design, integrate chemistry across sample types

Thank You

Angus Campbell

Cam Cairns

Shannon Herley

Charlotte Riley

Simon Travers

Nathan Reid

Cassady O'Neil

Robert Thorne

Brandon Mahon

- See Poster on Board P043 for accompanying poster
- Soil and Groundwater reports to be released 2026 for free download