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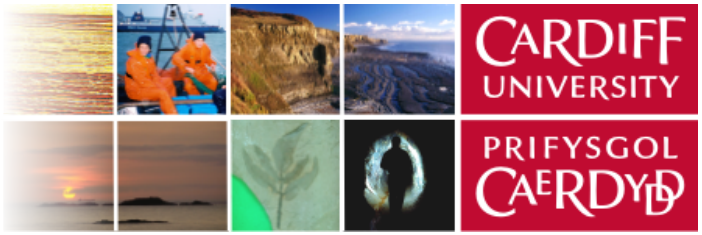

Greenhouse gas removal in the iron and steel industry

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NERC SCIENCE OF THE ENVIRONMENT

UKCCSRC – September 2017

Exploring the potential of GGR in existing industries

Iron and Steel

Cement

Lime

Caustics

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Cumulative Global CO_2 GGR potential (~2100)

Industry	Mineral Carbonate ($GtCO_2$)	Bicarbonate ($GtCO_2$)
Iron and steel slag	50	85
Cement kiln dust	25	42
Historically produced cement (1960 – 2015)	30	51
Caustics (paper & aluminium industry)	5	9
Lime	55	94
Total	**170**	**289**

Total GGR that may be required = 140 – 800 $GtCO_2$
[Edenhofer et al., 2014]

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Carbon Sequestration Reactions

Carbonation

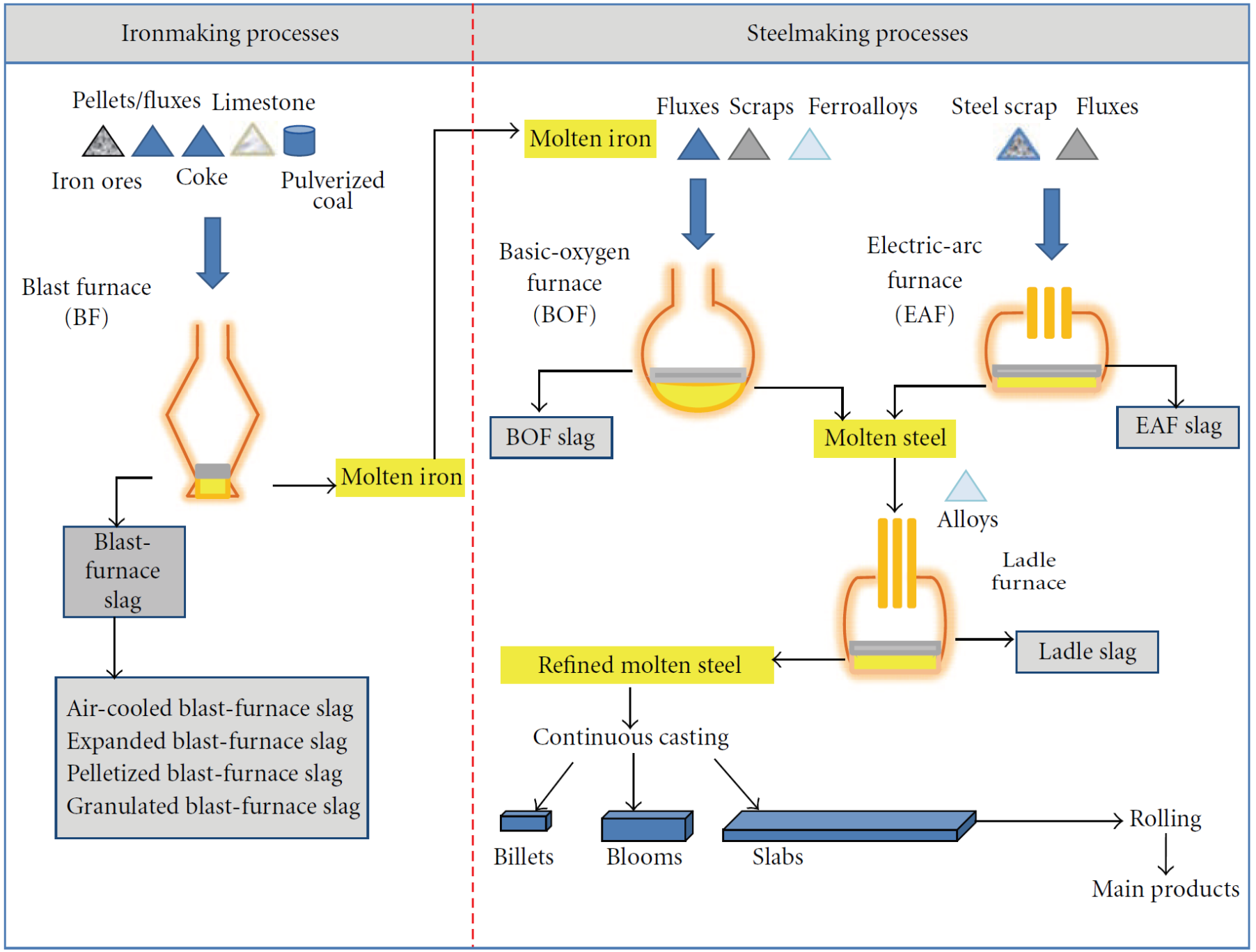
$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

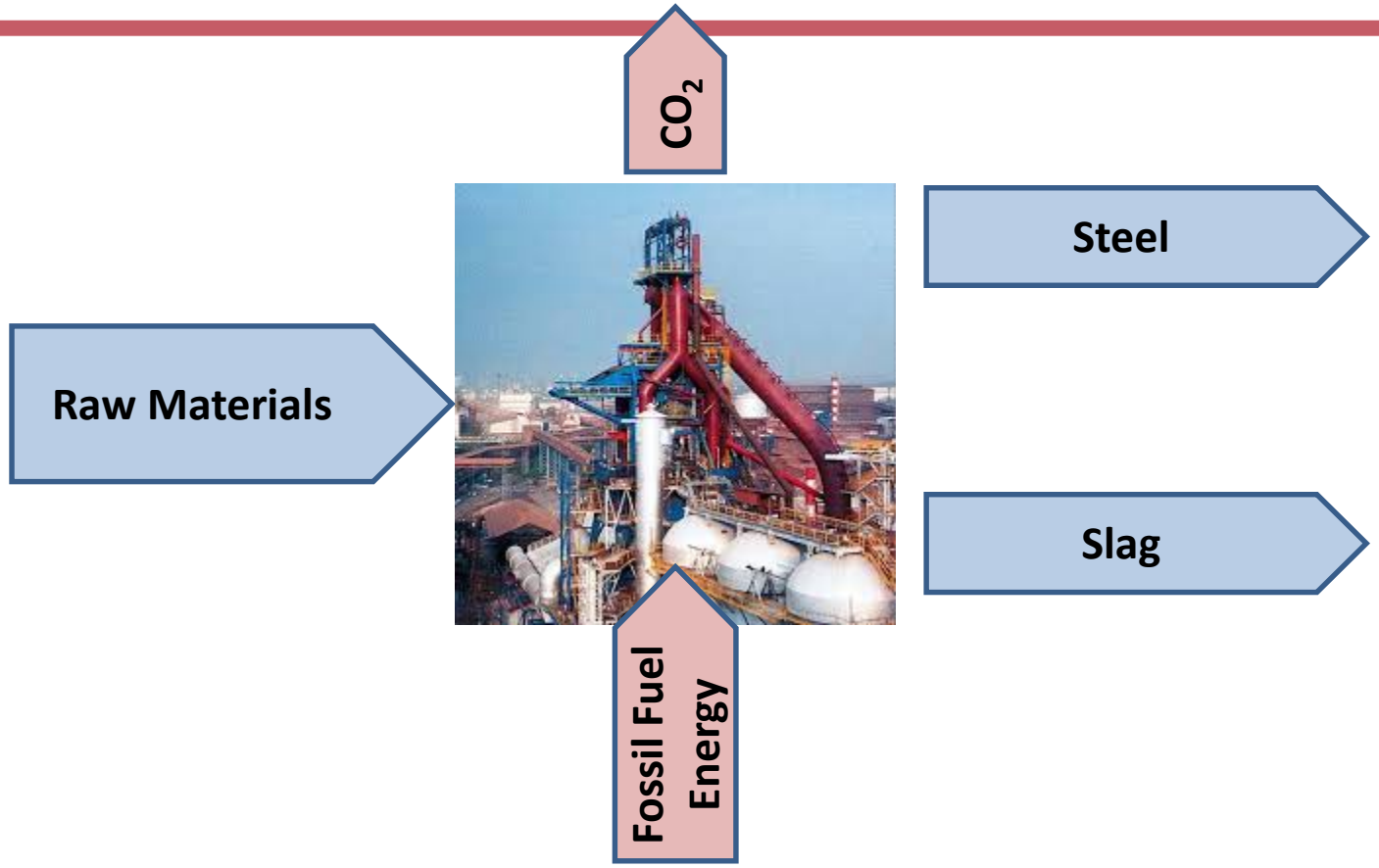
Renforth et al., (2009) Applied Geochemitry
Renforth et al., (2011) Environ. Sci. and Tech.

Ocean Alkalinity

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$$

Renforth and Henderson (2017) Rev. of Geophysics


Ironmaking processes
Steelmaking processes
Pellets/fluxes
Limestone
Iron ores
Coke
Pulverized coal
Blast furnace (BF)
Molten iron
Blast-furnace slag
Air-cooled blast-furnace slag
Expanded blast-furnace slag
Pelletized blast-furnace slag
Granulated blast-furnace slag
Molten iron
Fluxes
Scraps
Ferroalloys
Steel scrap
Fluxes
Basic-oxygen furnace (BOF)
Electric-arc furnace (EAF)
BOF slag
Molten steel
EAF slag
Alloys
Ladle furnace
Ladle slag
Refined molten steel
Continuous casting
Billets
Blooms
Slabs
Rolling
Main products



From IPCC AR5

In 2010 2.1 tCO_2 / tCrude Steel --or-- 5.7 tCO_2 / t(slag)

By 2050 0.6 tCO_2 / tCrude Steel --or-- 1.6 tCO_2 / t(slag)

CCS + Decarb Power 0.2 tCO_2 / tCrude Steel --or-- 0.5 tCO_2 / t(slag)

A net negative 0.2 tCO_2 per tCrude Steel could equate to 1 $GtCO_2$/yr GGR by 2050

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What is slag?

Table 2: Mineralogical phases of BOF, EAF, and ladle slags.

Reference	Slag	Mineralogical phases
Barra et al. [16]	EAF	$CaCO_3$, FeO, MgO, Fe_2O_3, $Ca_2Al(AlSiO_7)$, Ca_2SiO_4
Geiseler [29]	—	$2CaO \cdot SiO_2$, $3CaO \cdot SiO_2$, $2CaO \cdot Fe_2O_3$, FeO, (Ca, Fe)O (calciowustite), (Mg, Fe)O (magnesiowustite), free MgO, CaO
Juckes [8]	BOF	C_3S, C_2S, C_2F, RO phase (FeO-MgO-CaO-FeO), MgO, CaO
Luxán et al. [17]	EAF	Ca_2SiO_5, $Ca_2Al(AlSiO_7)$, Fe_2O_3, $Ca_{14}Mg_2(SiO_4)_8$, $MgFe_2O_4$, Mn_3O_4, MnO_2
Manso et al. [28]	Ladle	Al_2O_4Mg, $Ca(OH)_2$, Si_2O_6CaMg, MgO, Ca_3SiO_5, β-Ca_2SiO_4, γ-Ca_2SiO_4, SO_4Ca
Nicolae et al. [20]	BOF	$2CaO \cdot Al_2O_3 \cdot SiO_2$, Fe_2O_3, CaO, FeO
Nicolae et al. [20]	EAF	MnO_2, MnO, Fe_2SiO_4, Fe_7SiO_{10}
Nicolae et al. [20]	Ladle	$CaO \cdot SiO_2$, $CaOAl_2O_3 \cdot 2SiO_2$, CaS, Al_2O_3
Qian et al. [21]	EAF	γ-Ca_2SiO_4, C_3MS_2, CFMS, FeO-MnO-MgO solid solution
Qian et al. [21]	Ladle	γ-Ca_2SiO_4, C_3MS_2, MgO
Reddy et al. [25]	BOF	$2CaO \cdot Fe_2O_3$, $2CaO \cdot P_2O_5$, $2CaO \cdot SiO_2$, CaO
Reddy et al. [25]	BOF[q]	$2CaO \cdot Fe_2O_3$, $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, Fe_2O_3
Tossavainen et al. [13]	Ladle	$Ca_{12}Al_{14}O_{33}$, $MgO \cdot \beta$-Ca_2SiO_4, γ-Ca_2SiO_4, $Ca_2Al_2SiO_7$
Tossavainen et al. [13]	BOF	β-Ca_2SiO_4, FeO-MnO-MgO solid solution, MgO
Tossavainen et al. [13]	EAF	$Ca_3Mg(SiO_4)_2$, β-Ca_2SiO_4, Spinel solid solution $(Mg, Mn)(Cr, Al)_2O_4$, wustite-type solid solution ((Fe, Mg, Mn)O), $Ca_2(Al, Fe)_2O_5$
Tsakiridis et al. [19]	EAF	Ca_2SiO_4, $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, $Ca_2Al(AlSiO_7)$, Ca_3SiO_5, $2CaO \cdot Al_2O_3 \cdot SiO_2$, FeO, Fe_3O_4, MgO, SiO_2
Wachsmuth et al. [30]	BOF	Ca_2SiO_4, Ca_3SiO_5, FeO, $2CaO \cdot Fe_2O_3$

[q] quenched; — = type of slag not provided.

11 Studies - ~ 25 different phases

(Ca,Mg,Fe) – Silicates & Oxides

Some partial recarbonation (i.e. carbonates)

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Weathering of a historic heap

Consett in County Durham, UK

Former iron (and steelworks) ~1840's to 1980

Millions of tonnes of 'slag' produced

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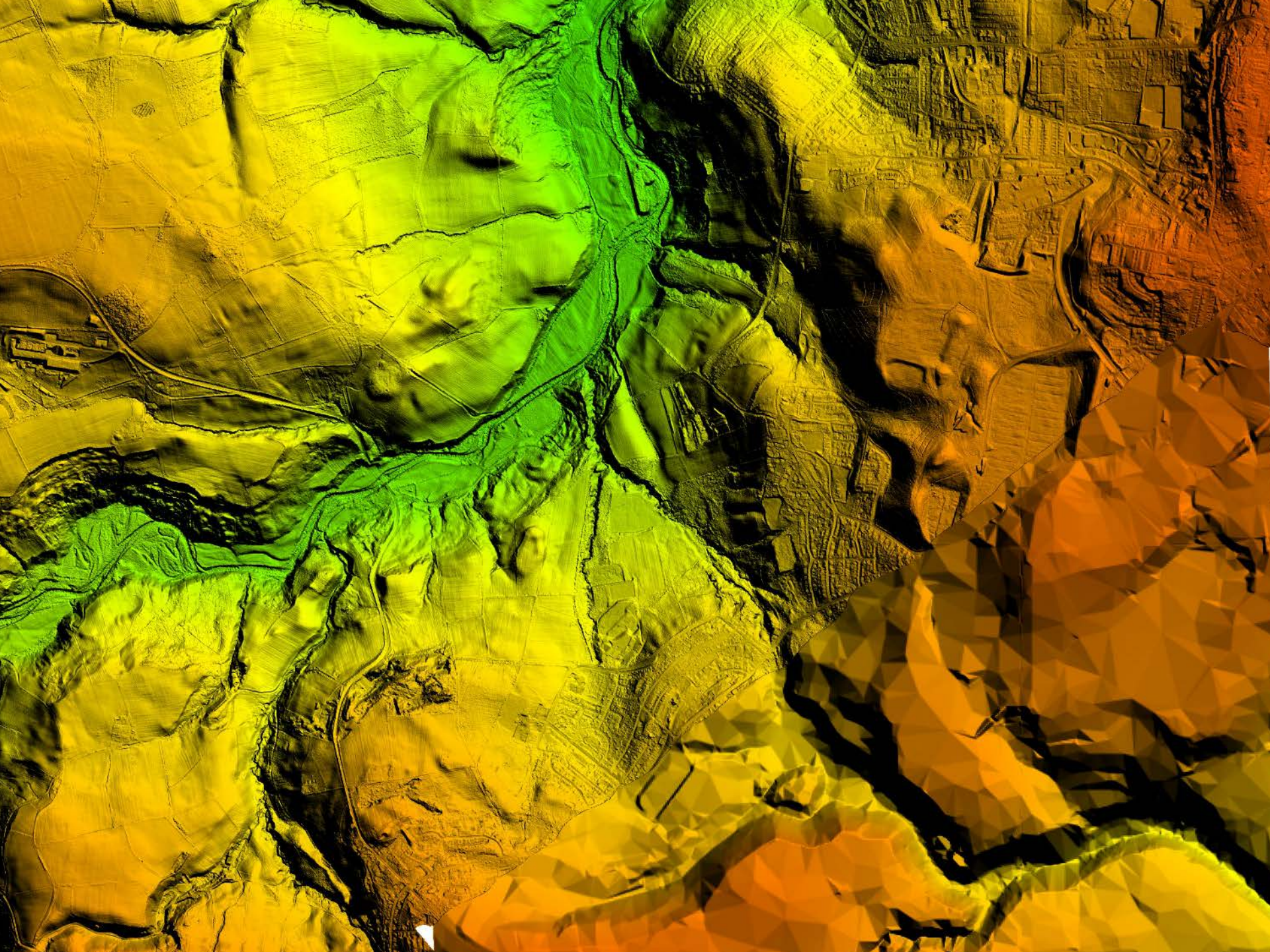

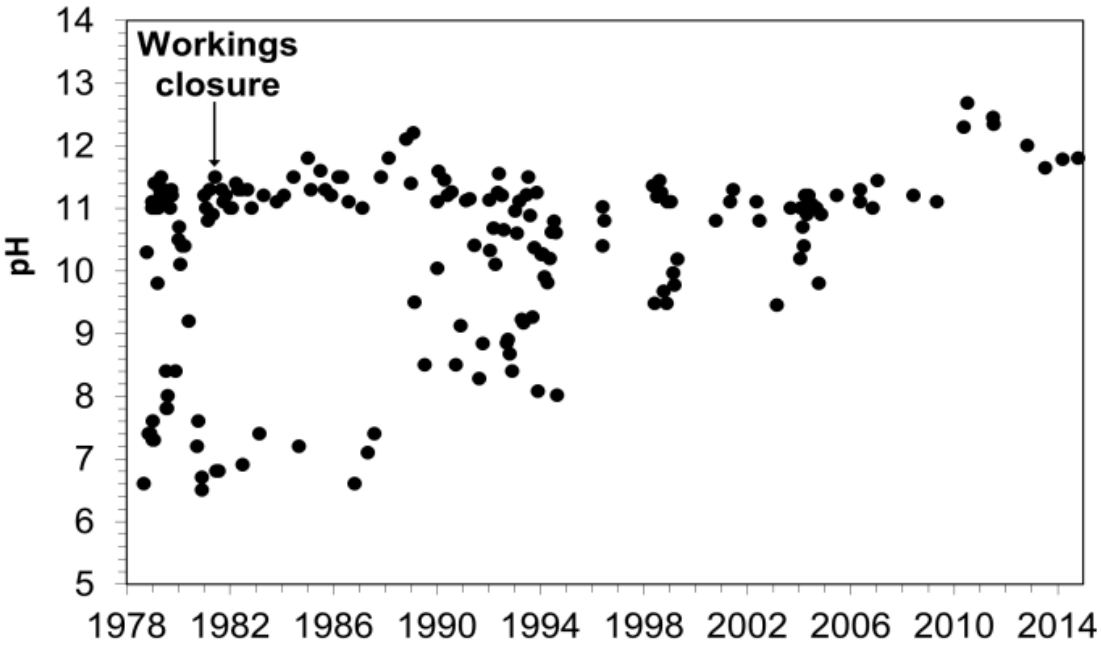

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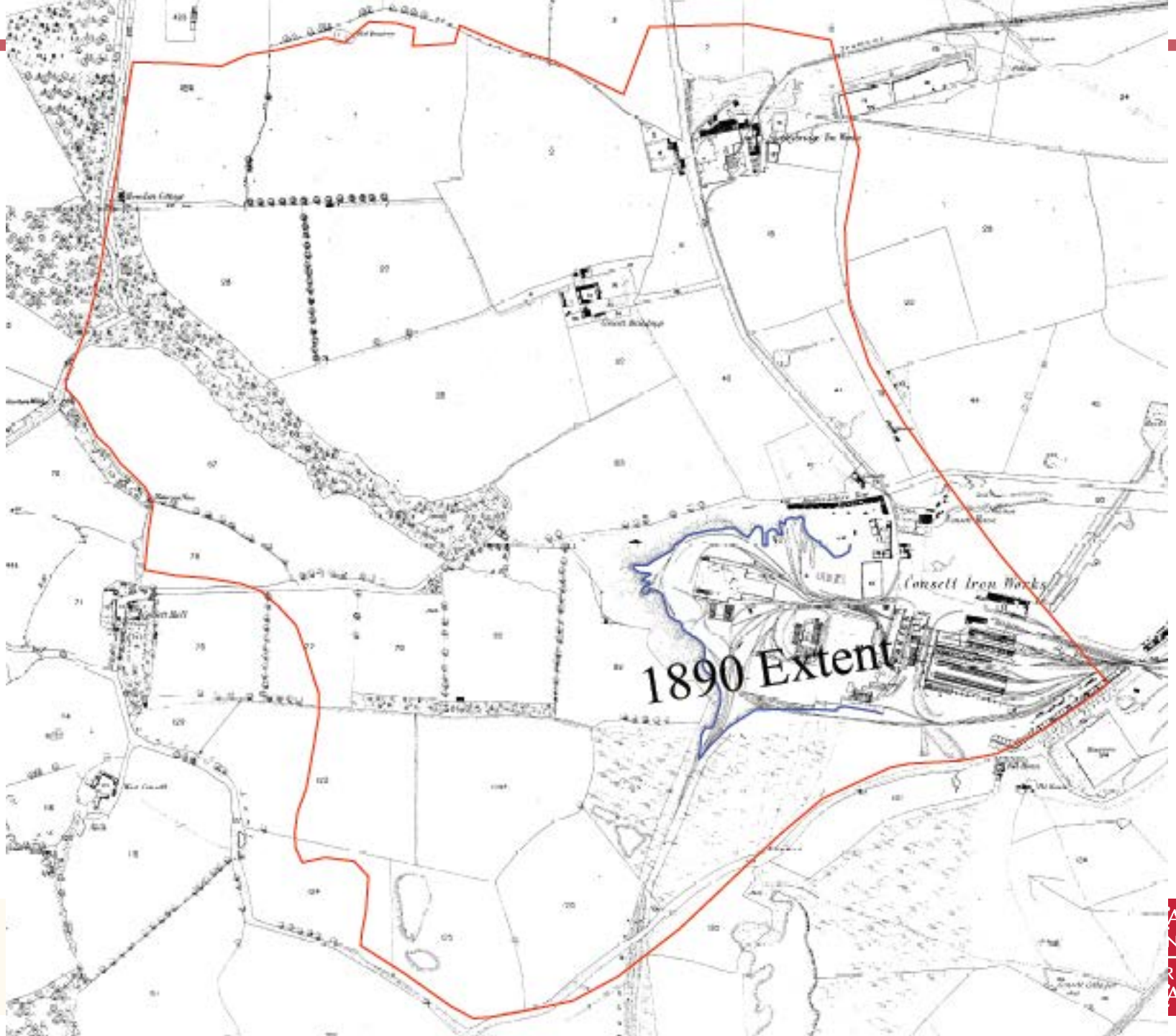
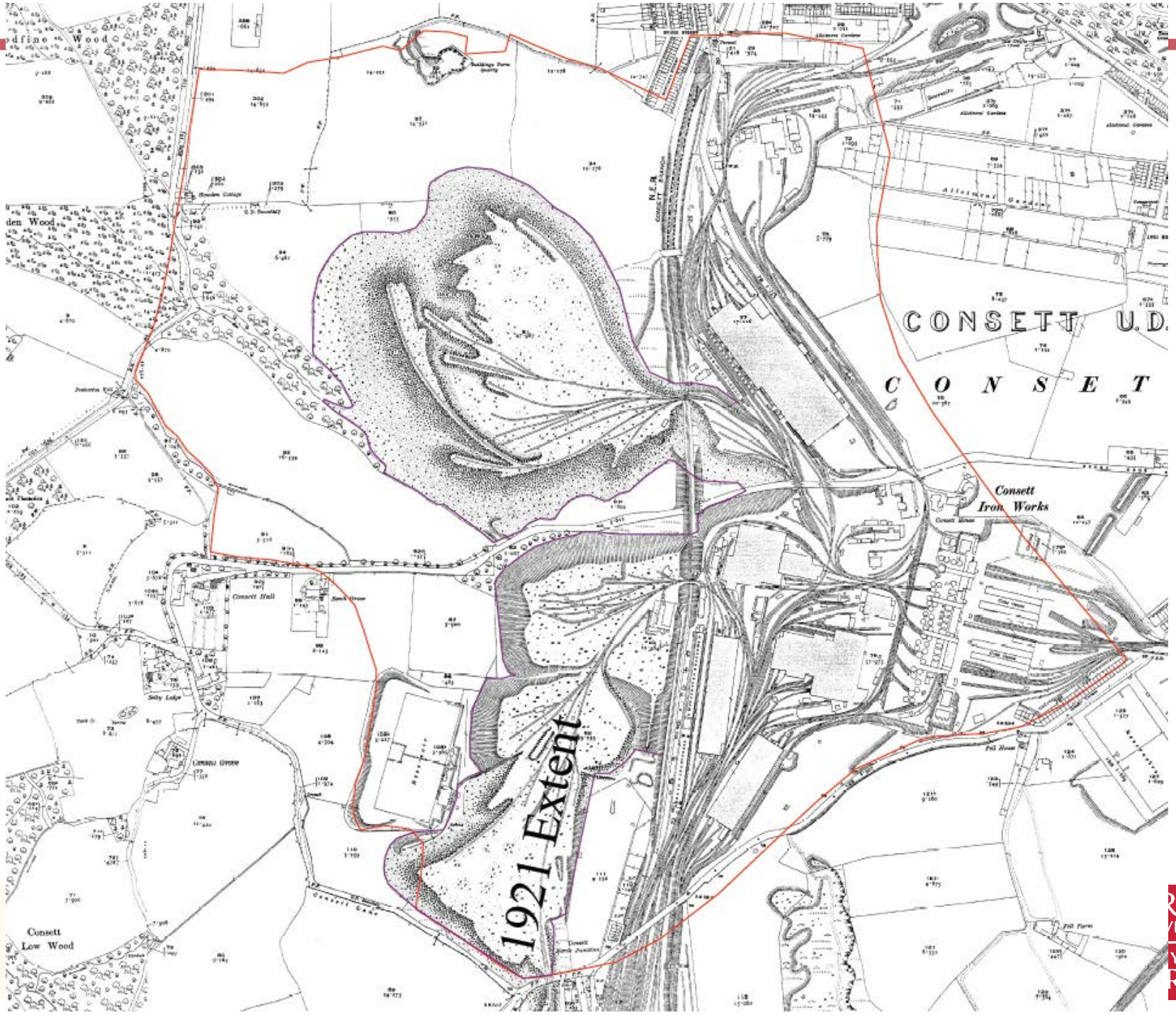
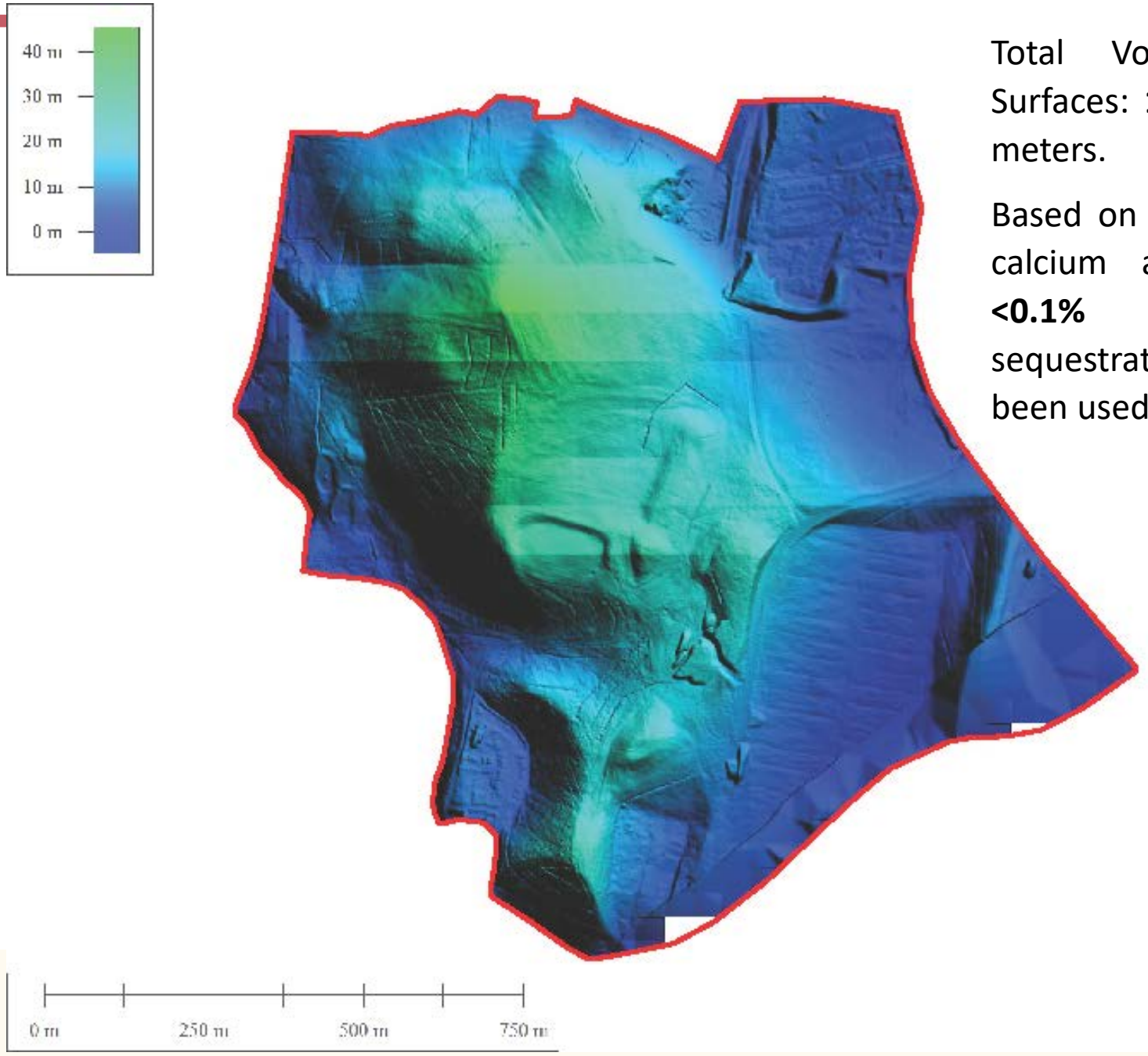

Consett Iron Works
1890 Extent


1921 Extent
CONSETT U.D.
C O N S E T T
Consett Iron Works
Consett Hall
Consett Low Wood
Silky Lodge
Fell House
Fell Farm
N.E.R.
Allotment Gardens

CONSETT SOUTH WARD
THE GROVE
1963Extent



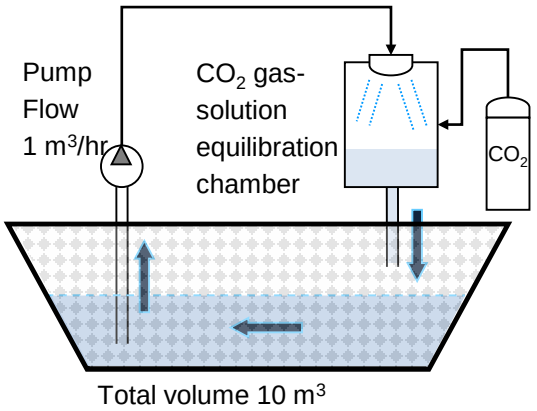
Total Volume Between Surfaces: **16,000,000** cubic meters.

Based on mass balance of calcium and magnesium **<0.1%** of carbon sequestration potential has been used.

Project Objectives

Work Package 1: Drilling and mineral/chemical characterisation

Work Package 2: batch heap weathering experiments



-Recirculation of water at a range of partial pressure CO_2

-Several solid material treatments

-Analysis of solution and solid chemistry

Work Package 3: Feasibility analysis – technoeconomic assessment + environmental impact

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PN65 KYA
GeoSonic

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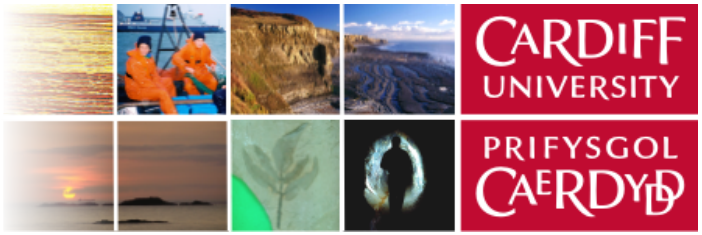

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