Geological, Geochemical and Mineralogical Characteristics of the Heavy Rare Earth-rich Carbonatites at Lofdal, Namibia

By

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OUTLINE OF THE PRESENTATION

1. Geological Setting of the Lofdal Alkaline Complex (LAC)

2. Lofdal intrusions

   Silicate intrusive rocks associated with the carbonatites

   Carbonatites at Lofdal

3. Geochemical Characteristics of the Lofdal carbonatites

4. Mineralogy of the Lofdal carbonatites

5. Comprehensive genesis of Lofdal carbonatites

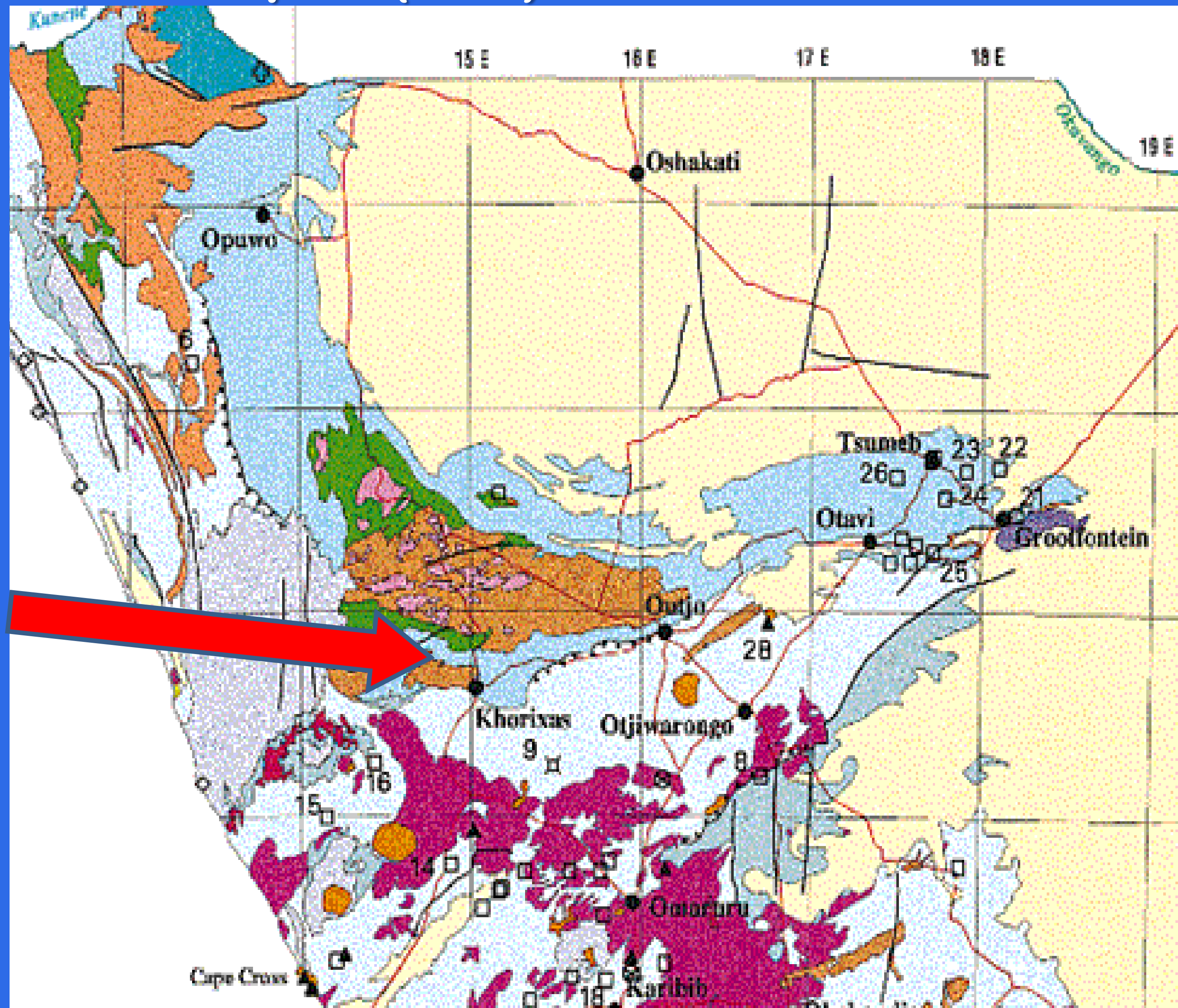
6. Comparison with World calciocarbonatites and REE-rich deposits

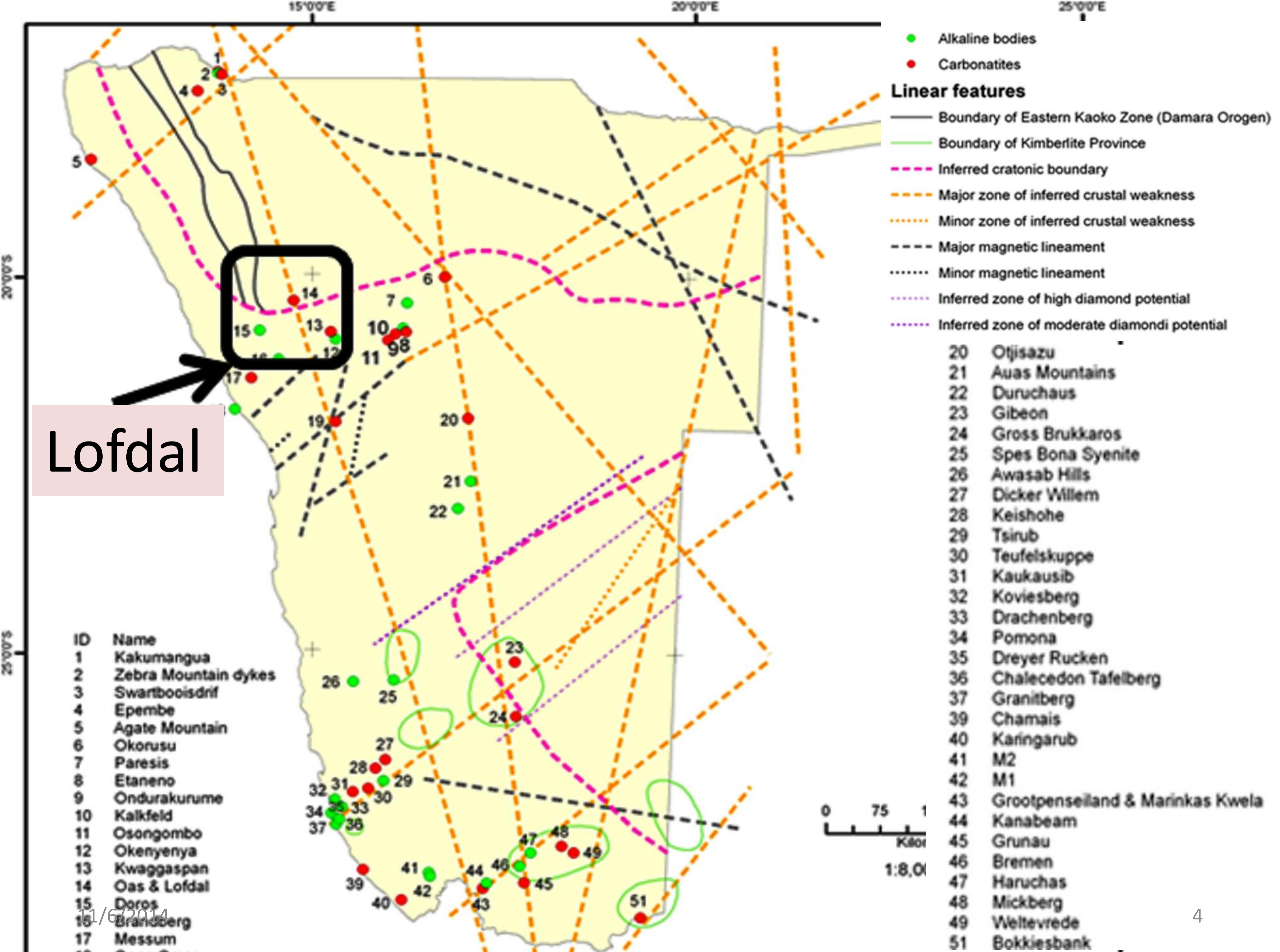
7. Conclusions

1. Regional Geological setting of the Lofdal Alkaline Complex (LAC)

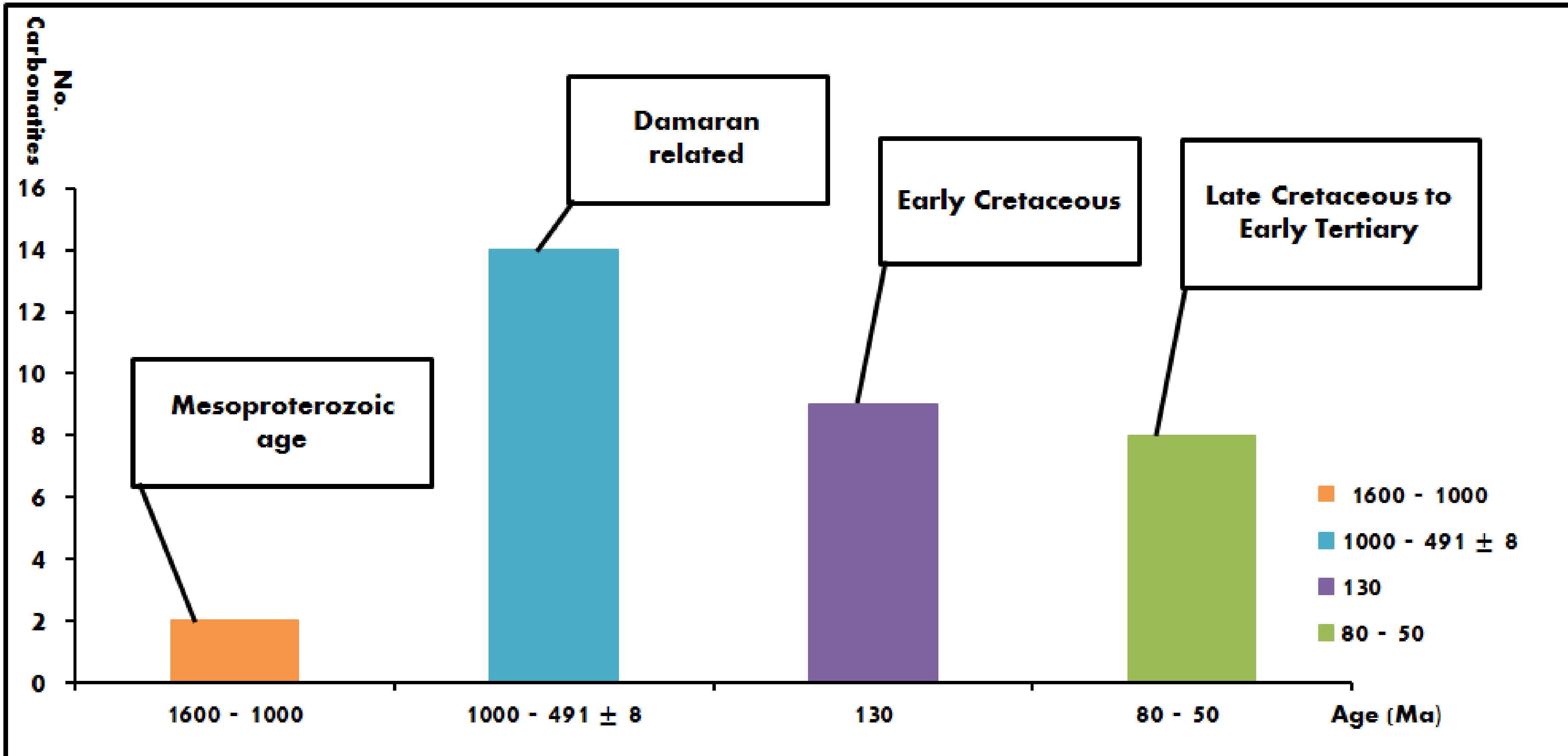
- Intruding inlier 2.0 Ga. HMC granitic and meta-sedimentary gneisses, amphibolites and related intrusions
- HMC variably metamorphosed at amphibolite grade
- Neoproterozoic (ca 765 Ma)

HMC = Huab Metamorphic Complex

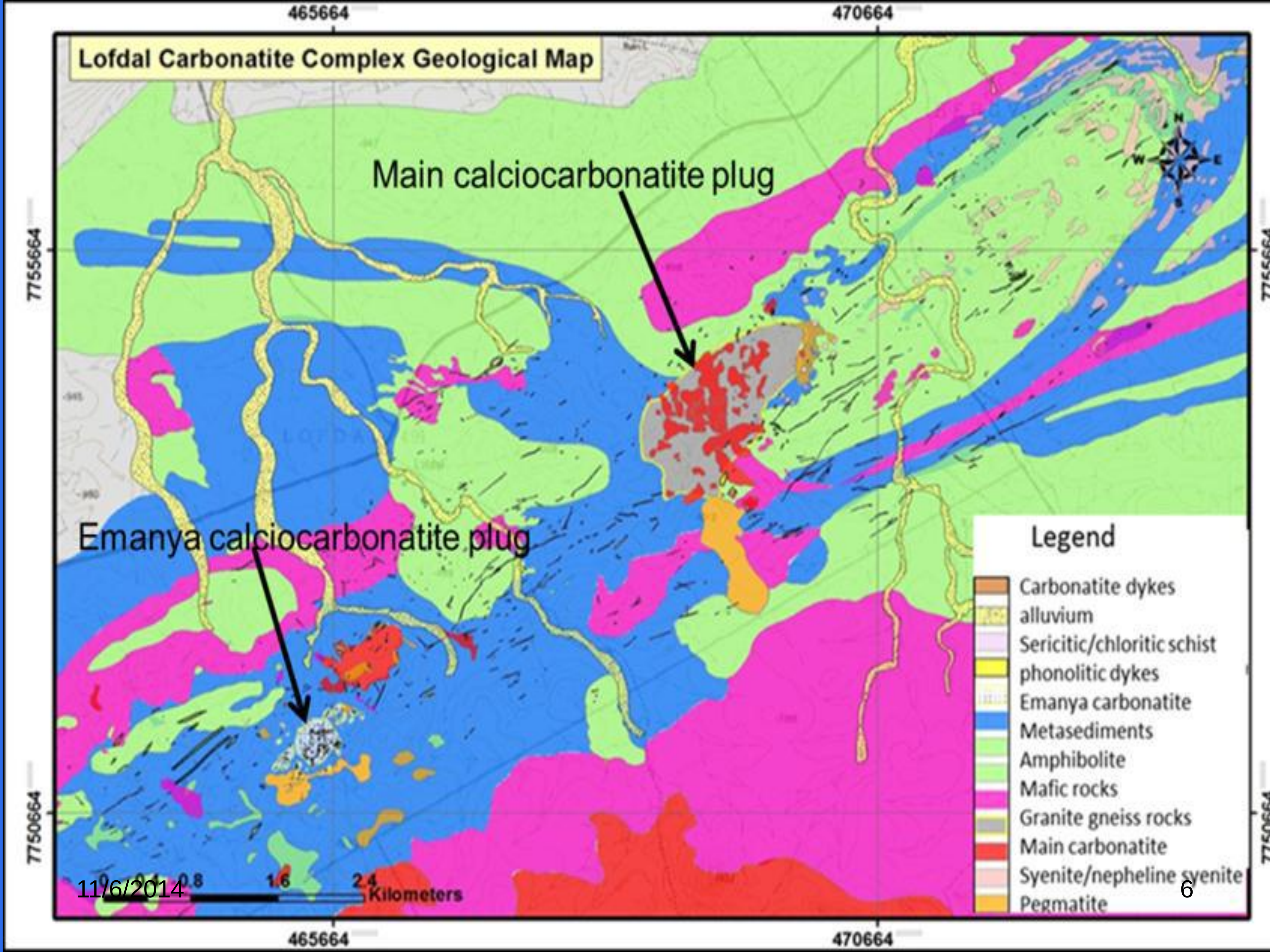



15°0'0"E
20°0'0"E
25°0'0"E
20°0'0"S
25°0'0"S
Lofdal
Alkaline bodies
Carbonatites
Linear features
Boundary of Eastern Kaoko Zone (Damara Orogen)
Boundary of Kimberlite Province
Inferred cratonic boundary
Major zone of inferred crustal weakness
Minor zone of inferred crustal weakness
Major magnetic lineament
Minor magnetic lineament
Inferred zone of high diamond potential
Inferred zone of moderate diamondi potential
ID Name
1 Kakumangua
2 Zebra Mountain dykes
3 Swartbooisdrif
4 Epembe
5 Agate Mountain
6 Okorusu
7 Paresis
8 Etaneno
9 Ondurakurume
10 Kalkfeld
11 Osongombo
12 Okenyenya
13 Kwaggaspan
14 Oas & Lofdal
15 Doros
16 Brandberg
17 Messum
18 Cape Cross
20 Otjisazu
21 Auas Mountains
22 Duruchaus
23 Gibeon
24 Gross Brukkaros
25 Spes Bona Syenite
26 Awasab Hills
27 Dicker Willem
28 Keishohe
29 Tsirub
30 Teufelskuppe
31 Kaukausib
32 Koviesberg
33 Drachenberg
34 Pomona
35 Dreyer Rucken
36 Chalecedon Tafelberg
37 Granitberg
39 Chamais
40 Karingarub
41 M2
42 M1
43 Grootpenseiland & Marinkas Kwela
44 Kanabeam
45 Grunau
46 Bremen
47 Haruchas
48 Mickberg
49 Weltevrede
51 Bokkiesbank
0 75
1:8,0

Frequency of Namibian carbonatite intrusions

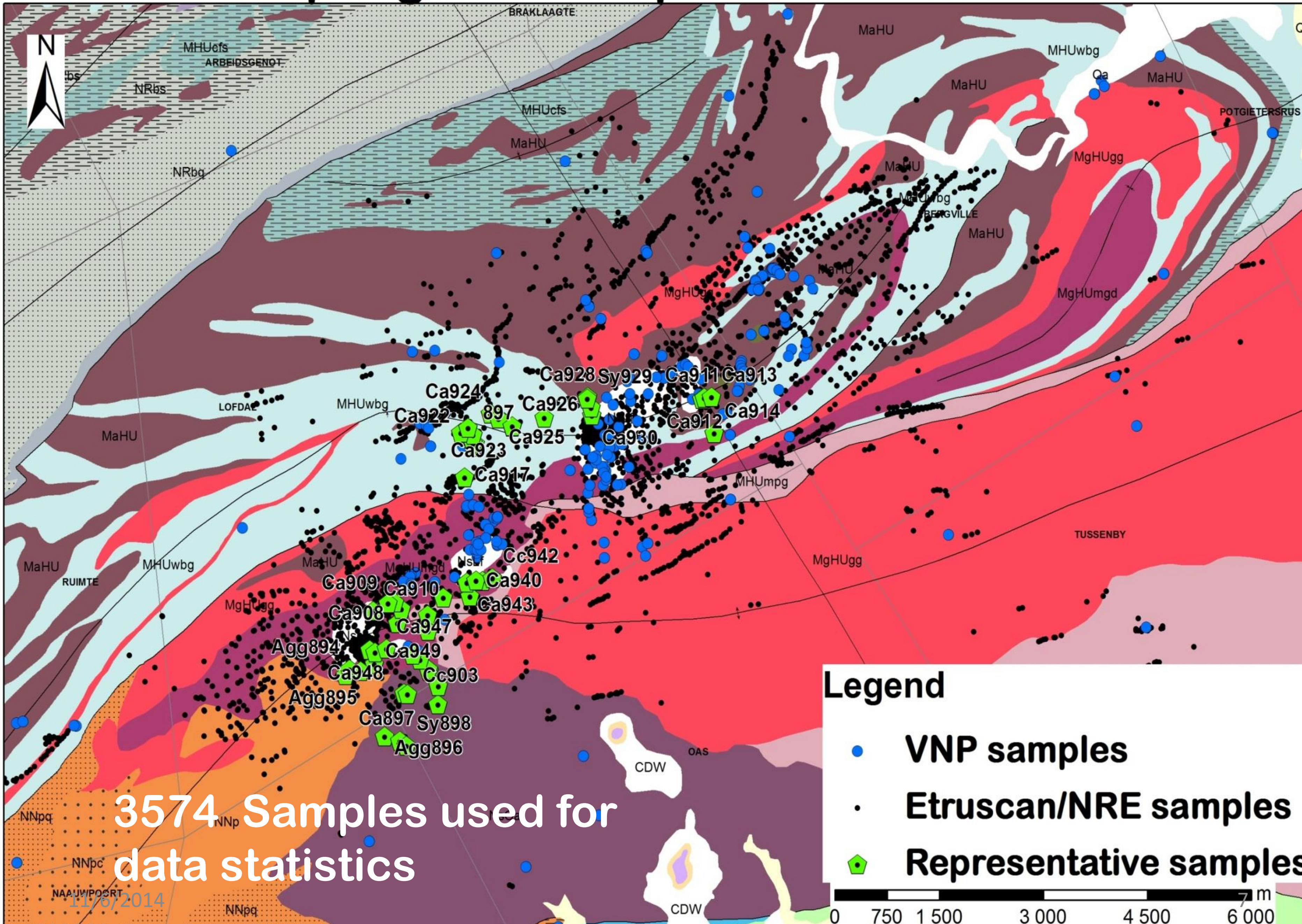


Lofdal 765 Ma

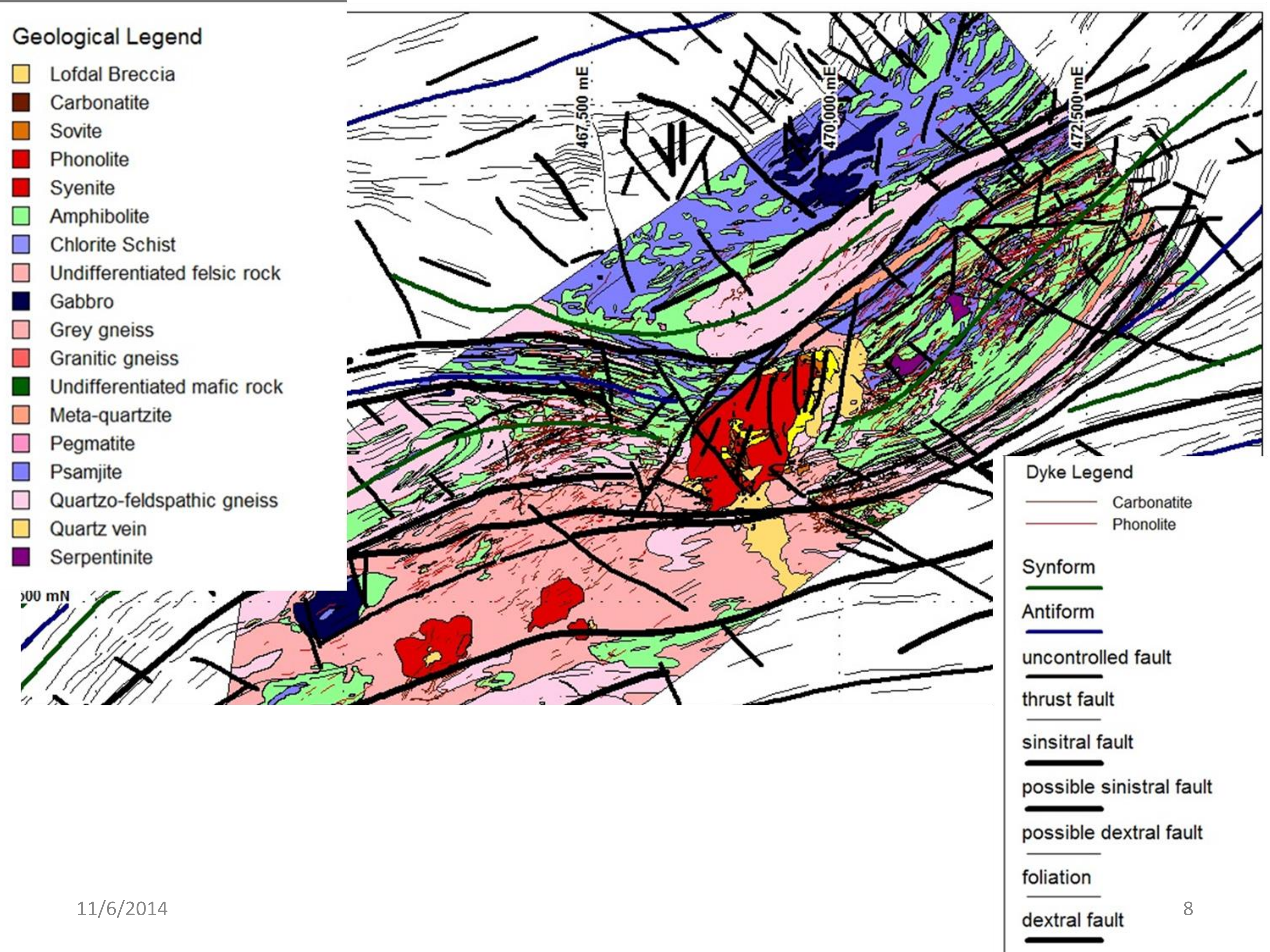


Lofdal Carbonatite Complex Geological Map
Main calciocarbonatite plug
Emanya calciocarbonatite plug
465664
470664
7755664
7750664
0 0.4 0.8 1.6 2.4
Kilometers
Legend
Carbonatite dykes
alluvium
Sericitic/chloritic schist
phonolitic dykes
Emanya carbonatite
Metasediments
Amphibolite
Mafic rocks
Granite gneiss rocks
Main carbonatite
Syenite/nepheline syenite
Pegmatite

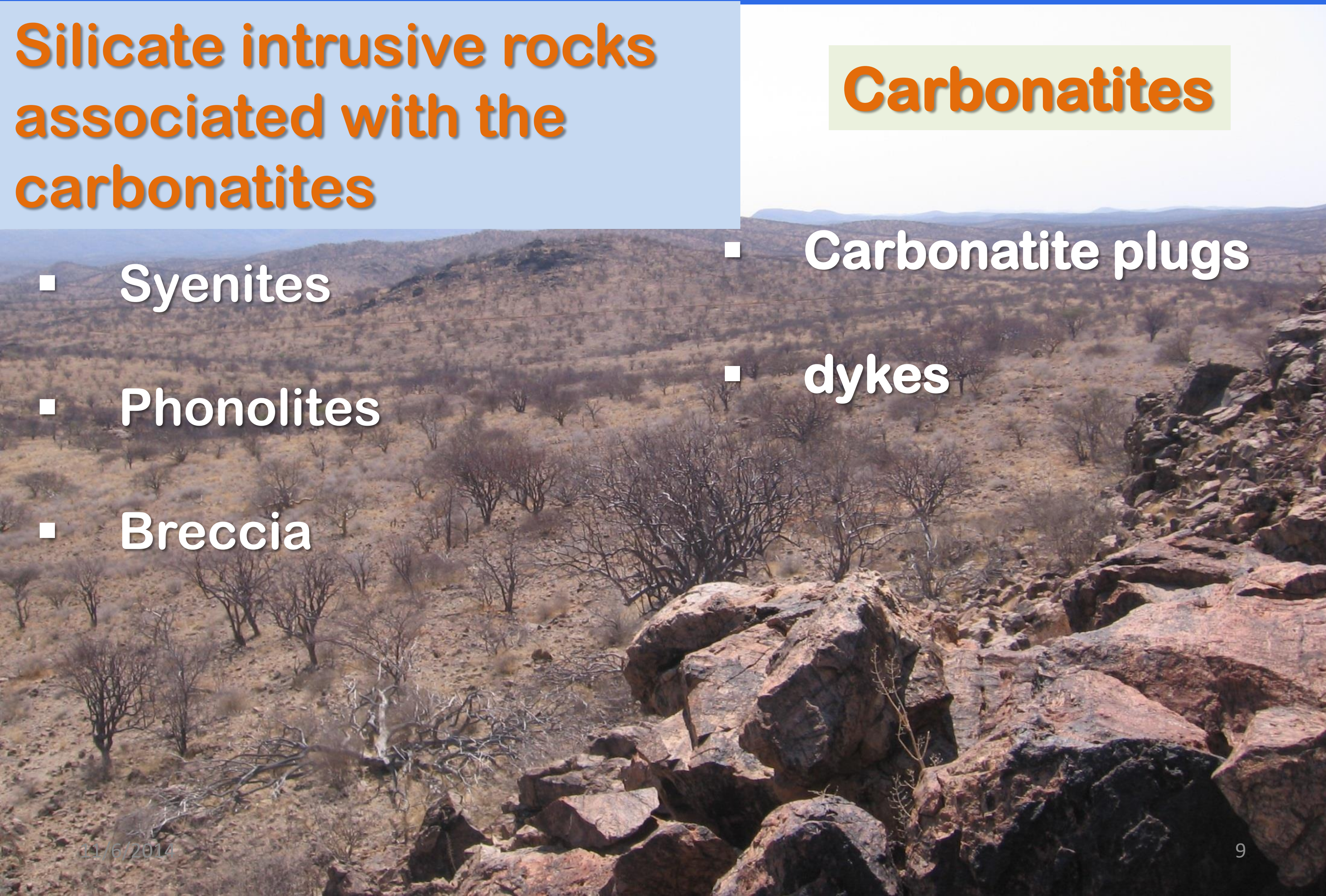
Sampling and Sample Distribution



3574 Samples used for data statistics


Geological Legend
Lofdal Breccia
Carbonatite
Sovite
Phonolite
Syenite
Amphibolite
Chlorite Schist
Undifferentiated felsic rock
Gabbro
Grey gneiss
Granitic gneiss
Undifferentiated mafic rock
Meta-quartzite
Pegmatite
Psamjite
Quartzo-feldspathic gneiss
Quartz vein
Serpentinite
467 500 mE
470 000 mE
472 500 mE
Dyke Legend
Carbonatite
Phonolite
Synform
Antiform
uncontrolled fault
thrust fault
sinistral fault
possible sinistral fault
possible dextral fault
foliation
dextral fault

2. Lofdal intrusions



Silicate intrusive rocks associated with the carbonatites

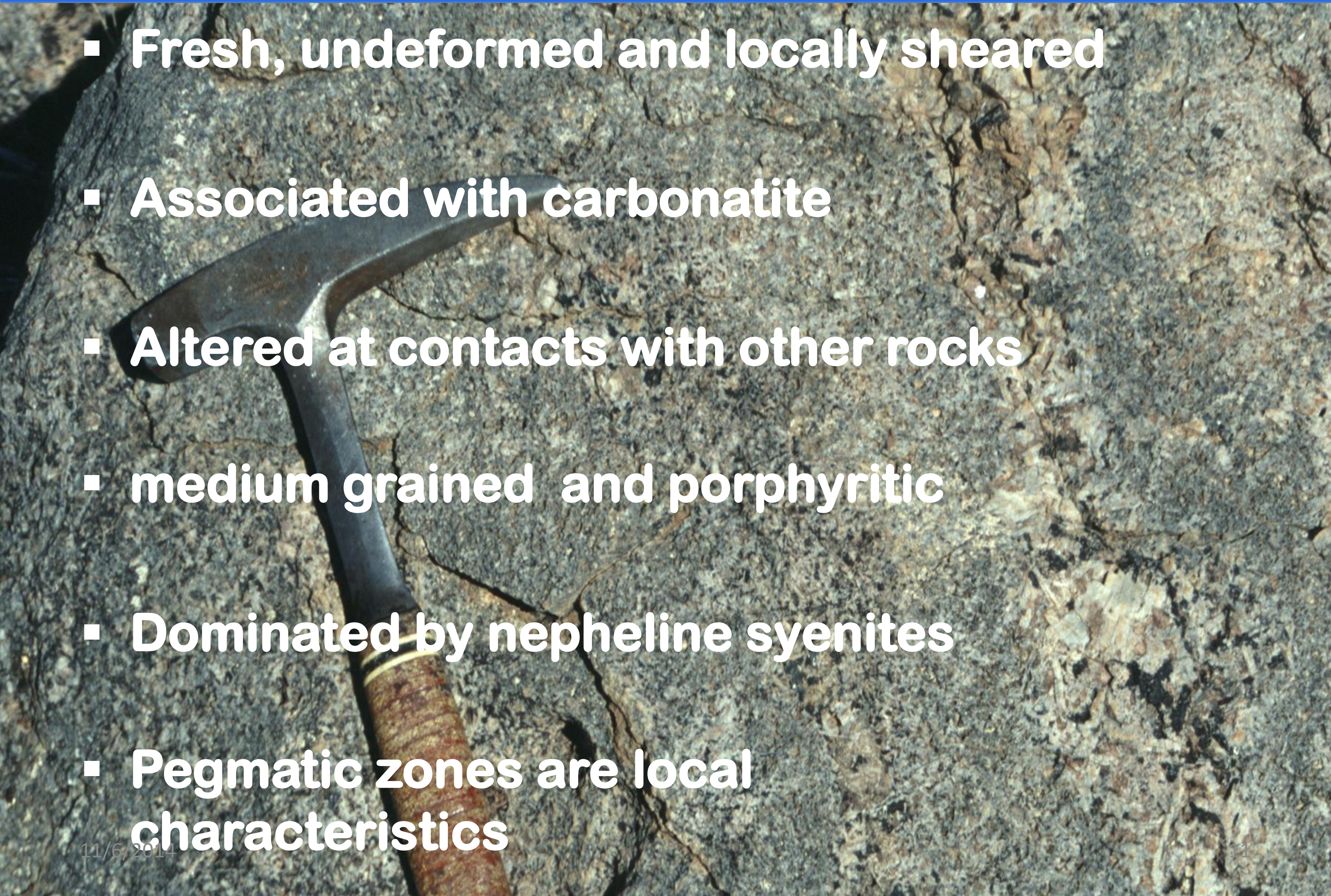
- Syenites
- Phonolites
- Breccia

Carbonatites

- Carbonatite plugs
- dykes

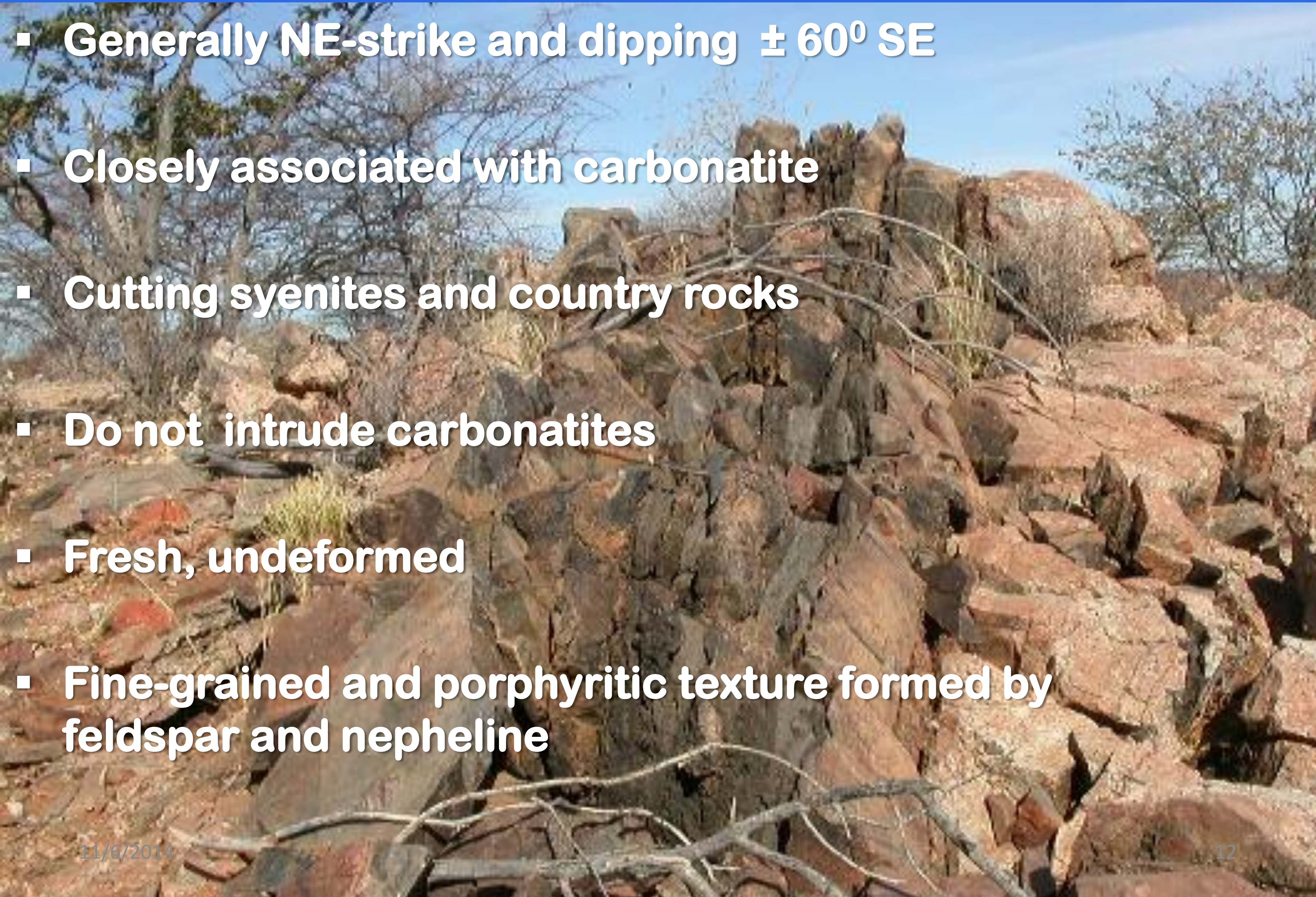
2. **Silicate intrusive rocks associated with the carbonatites:**

Syenites



- Fresh, undeformed and locally sheared
- Associated with carbonatite
- Altered at contacts with other rocks
- medium grained and porphyritic
- Dominated by nepheline syenites
- Pegmatic zones are local characteristics

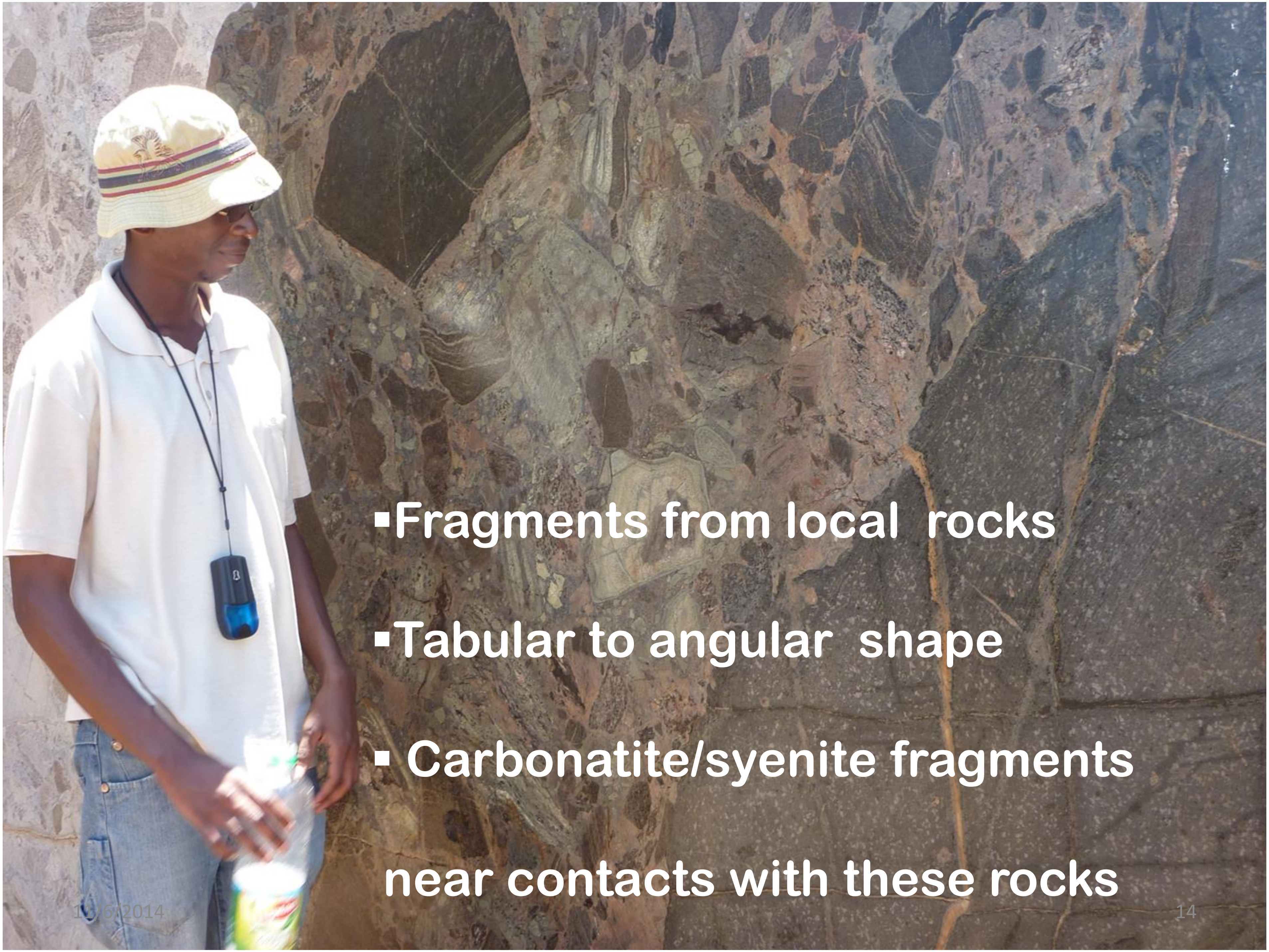
Phonolites



- Generally NE-strike and dipping ± 60^0 SE
- Closely associated with carbonatite
- Cutting syenites and country rocks
- Do not intrude carbonatites
- Fresh, undeformed
- Fine-grained and porphyritic texture formed by feldspar and nepheline

Breccia

- Preceded syenite but not carbonatites
- Polylithic breccia

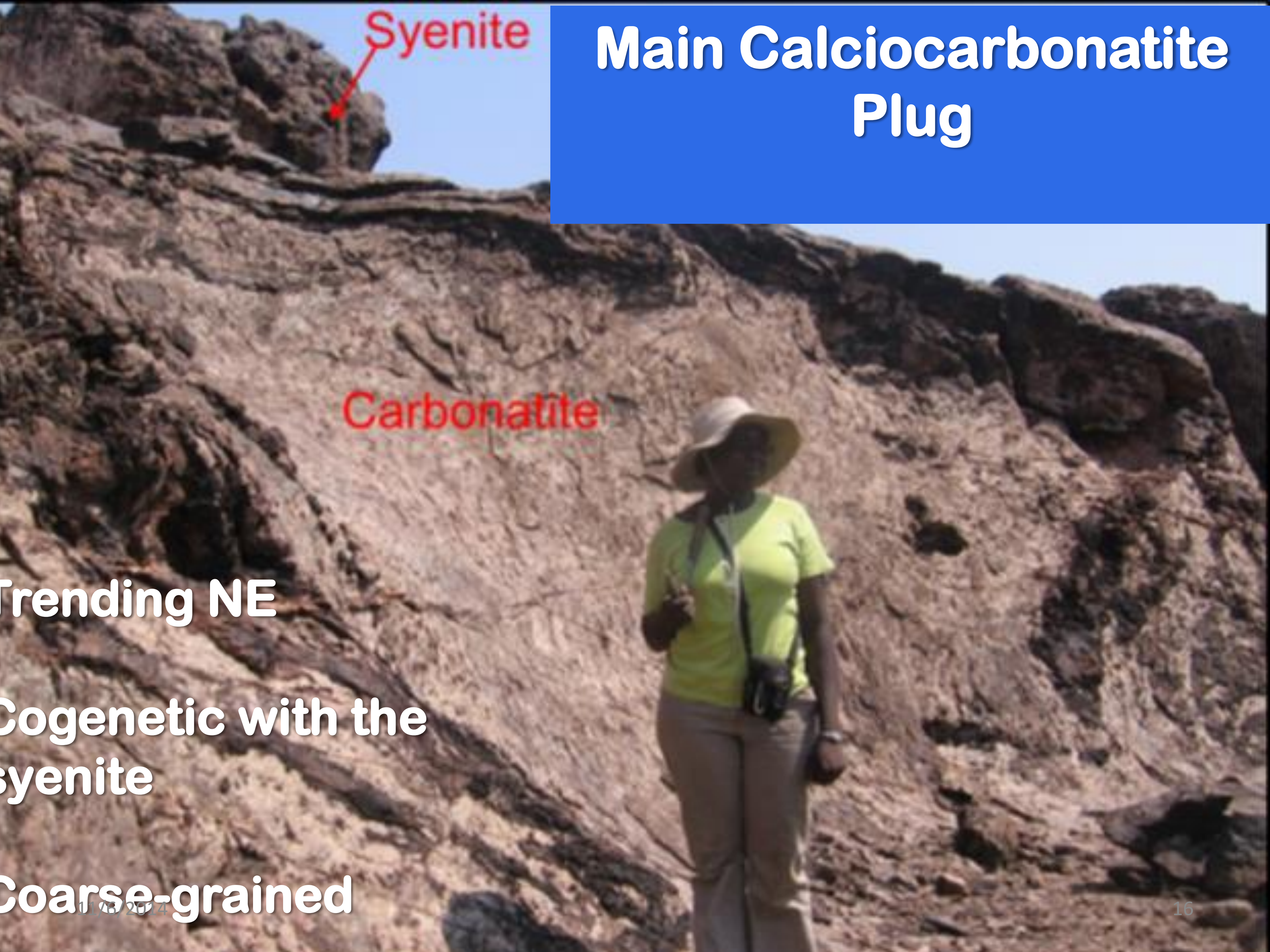


- Fragments from local rocks
- Tabular to angular shape
- Carbonatite/syenite fragments near contacts with these rocks

3. Carbonatites at Lofdal

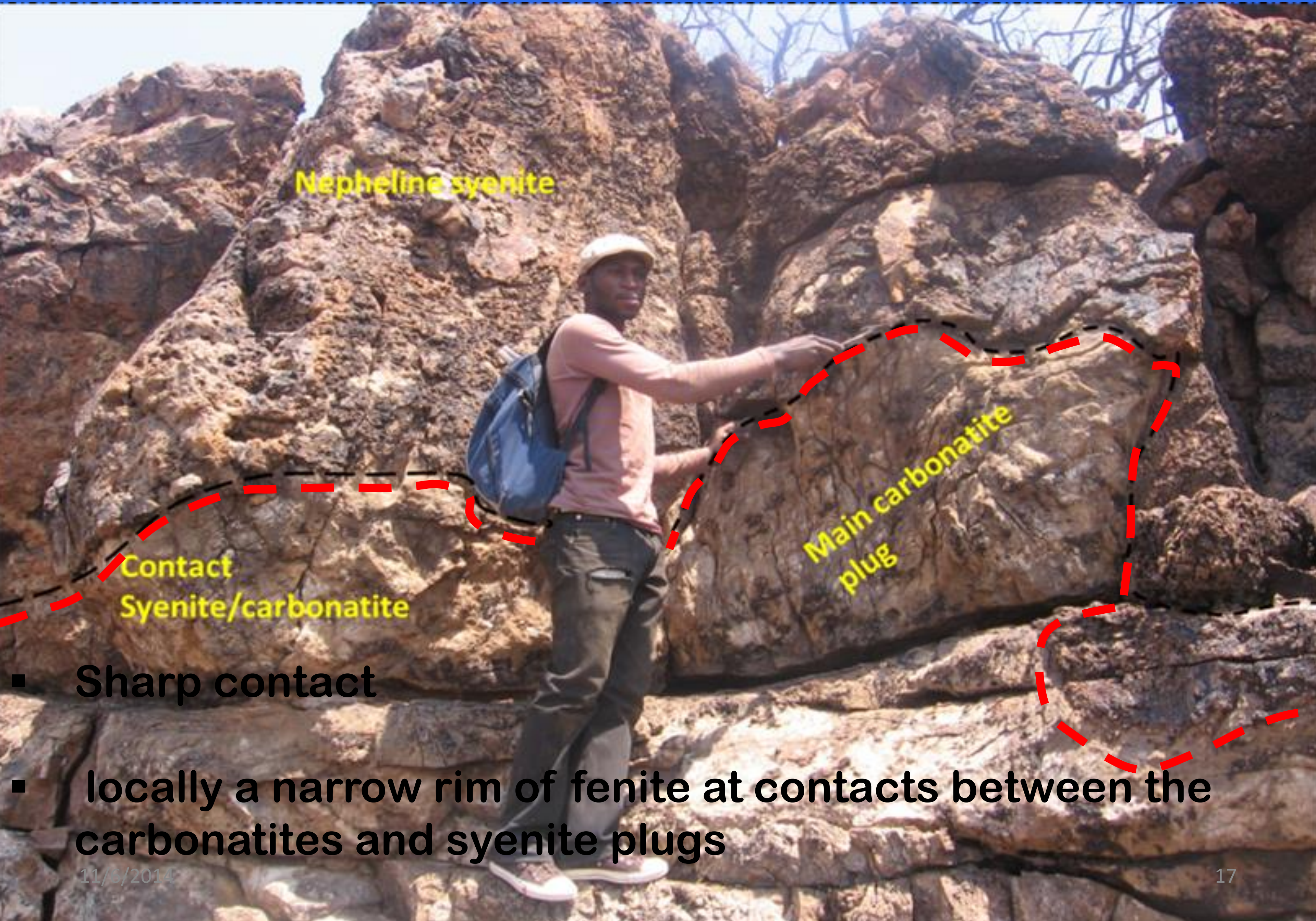
- Carbonatite plugs
- dykes

Main Calciocarbonatite Plug



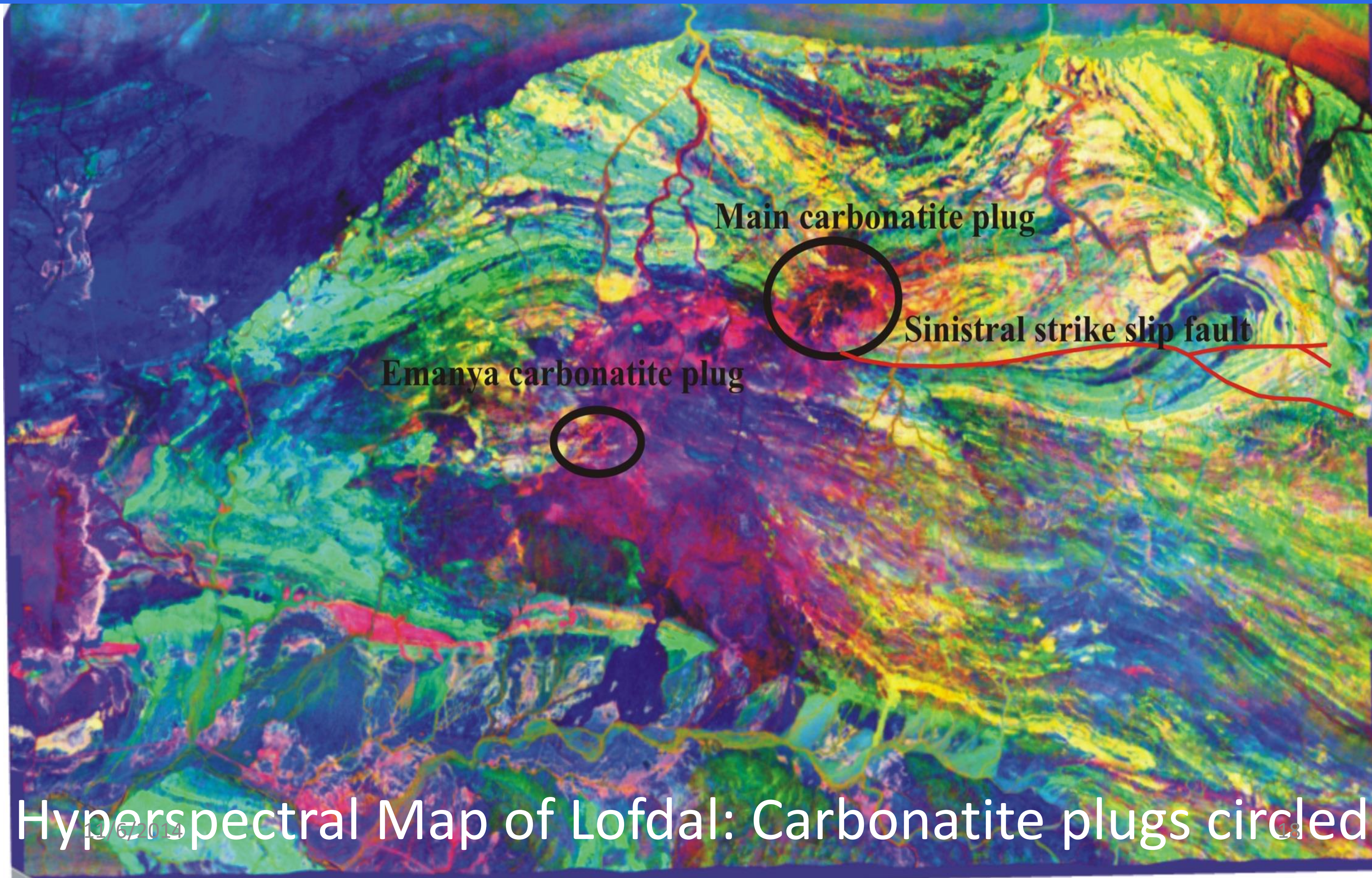
- Trending NE
- Cogenetic with the syenite
- Coarse-grained

Main Calciocarbonatite plug



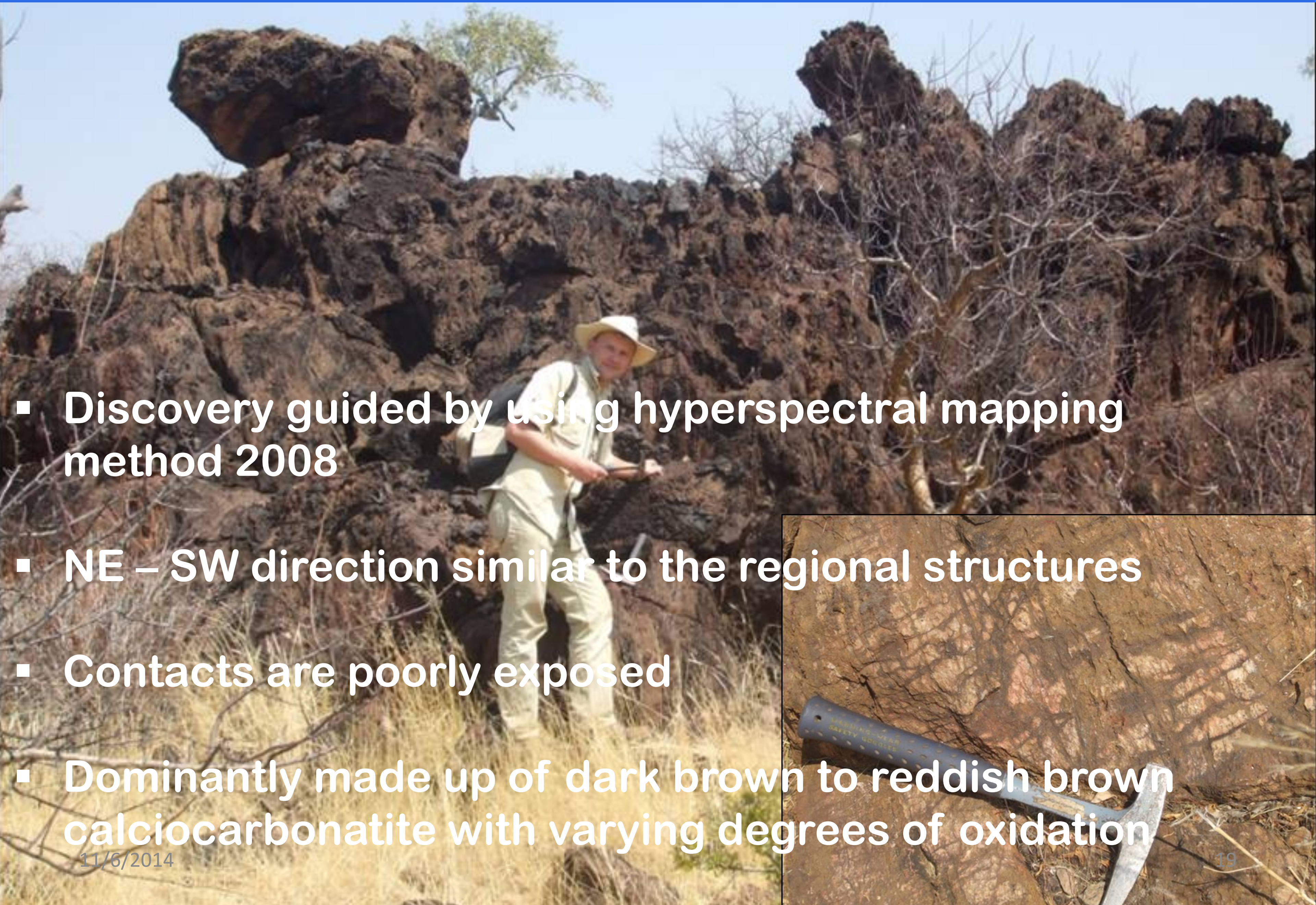
- Sharp contact
- locally a narrow rim of fenite at contacts between the carbonatites and syenite plugs

Emanya Calciocarbonatite plug



Hyperspectral Map of Lofdal: Carbonatite plugs circled

Emanya Calciocarbonatite plug



- Discovery guided by using hyperspectral mapping method 2008
- NE – SW direction similar to the regional structures
- Contacts are poorly exposed
- Dominantly made up of dark brown to reddish brown calciocarbonatite with varying degrees of oxidation

Carbonatite Dykes

Carbonatite Dykes

- Swarm of thousands of dykes stretching up to 30 km
- Dominantly NE, NNE and E/W striking
- Parallel to and closely associated with phonolites
- Crosscutting all of the other rocks
- Sharp contacts, locally with “leakage” into cracks and brecciated
- Sizes ranging from few cm to < 0.5 m average width
- Variable colours – grey, brown, red, yellow
- Variably deformed and sheared
- Unsystematic composition and variable mineral distribution

Main carbonatite intrusion

Grey carbonatite

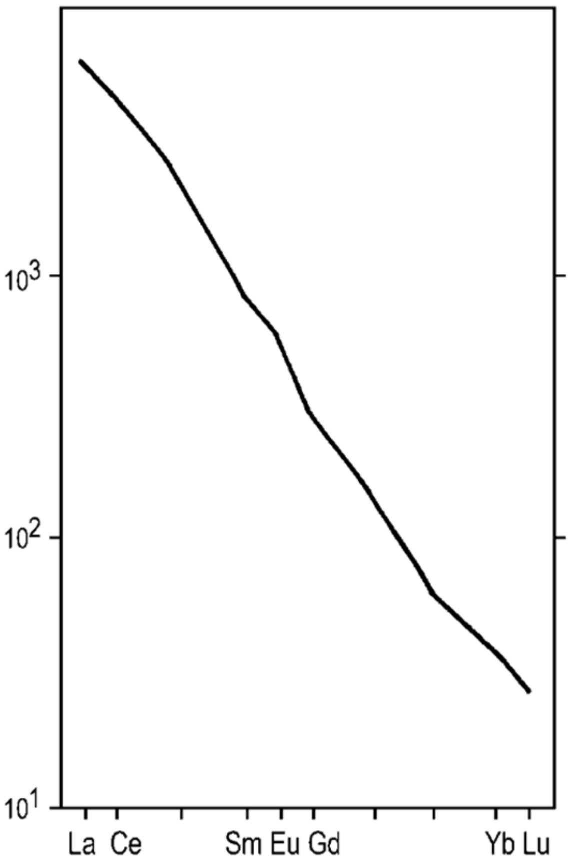
Highly oxidised ferruginous carbonatite

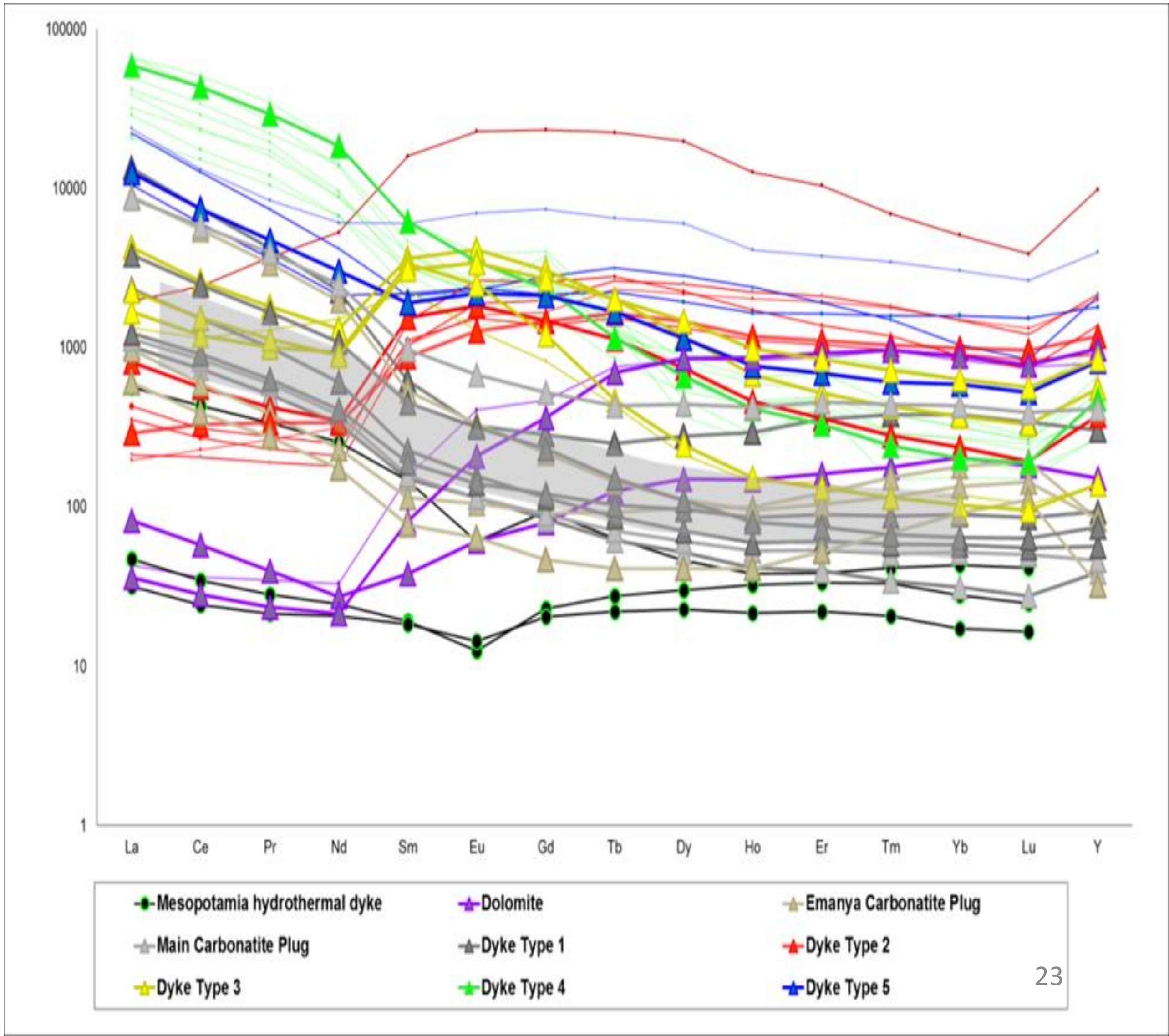
Late grey carbonatite

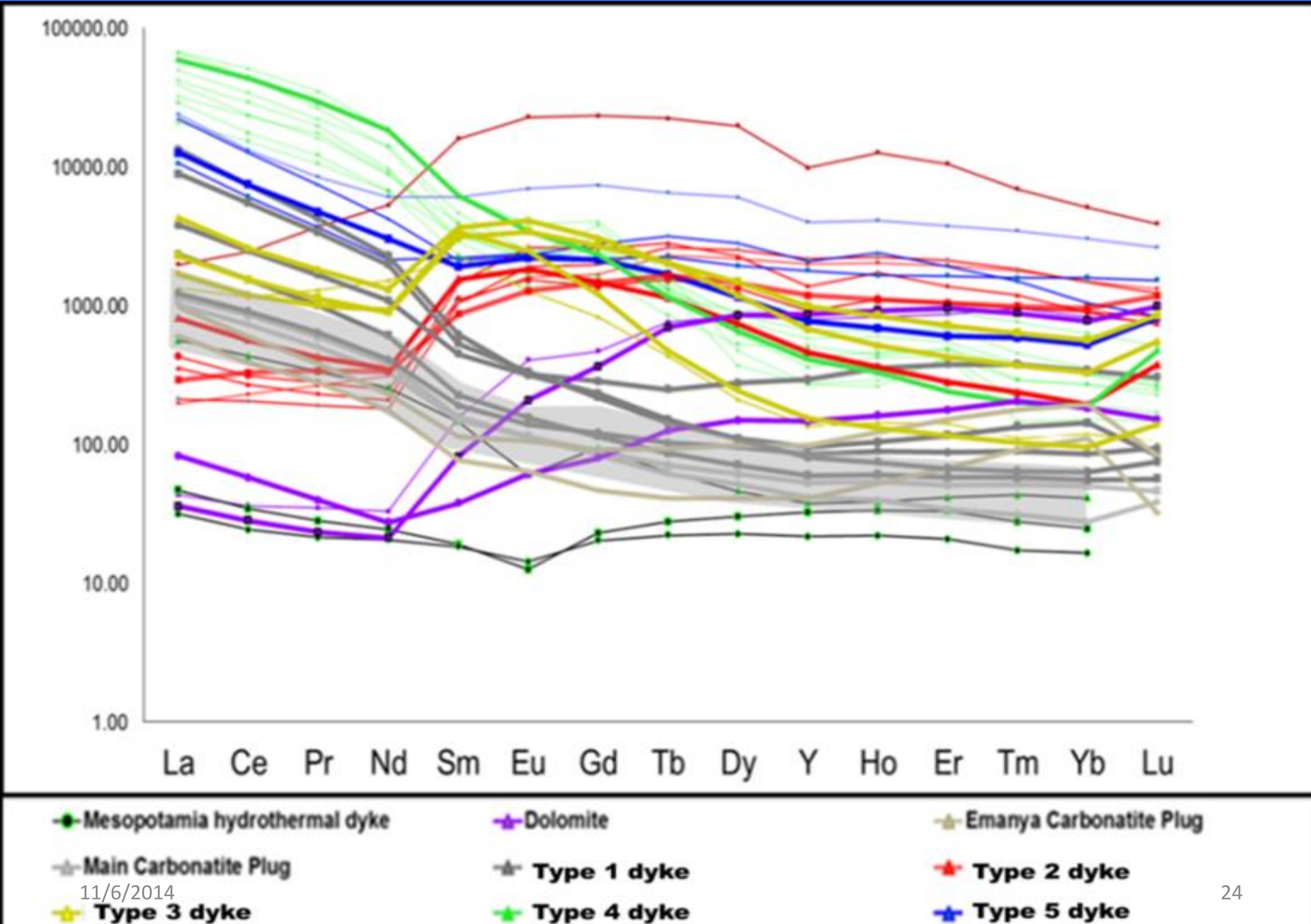
Hydrothermal carbonate

Dolomite carbonatite

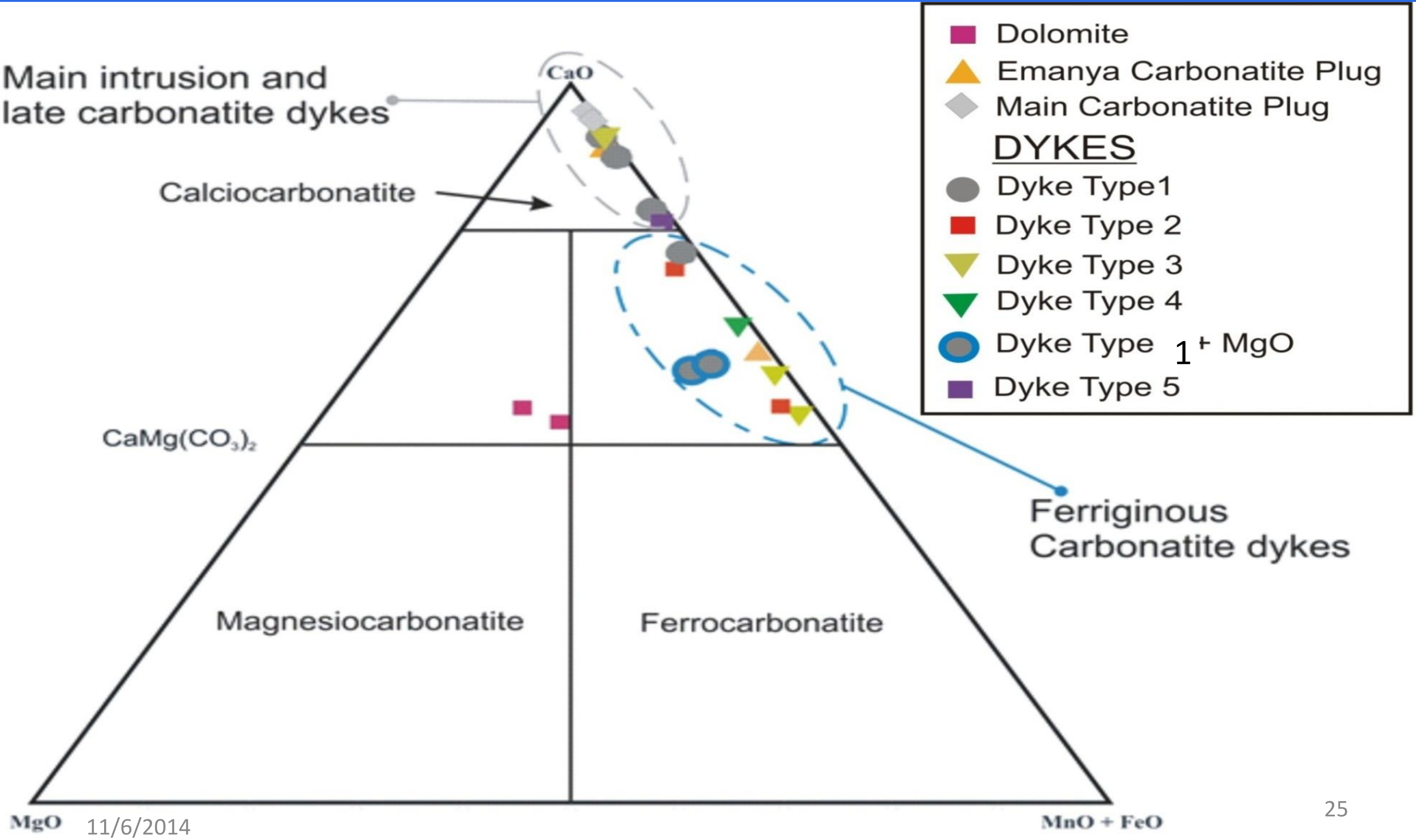
4. Geochemical classification of the Lofdal carbonatites






100000.00
10000.00
1000.00
100.00
10.00
1.00
La Ce Pr Nd Sm Eu Gd Tb Dy Y Ho Er Tm Yb Lu
Mesopotamia hydrothermal dyke
Dolomite
Emanya Carbonatite Plug
Main Carbonatite Plug
Type 1 dyke
Type 2 dyke
Type 3 dyke
Type 4 dyke
Type 5 dyke

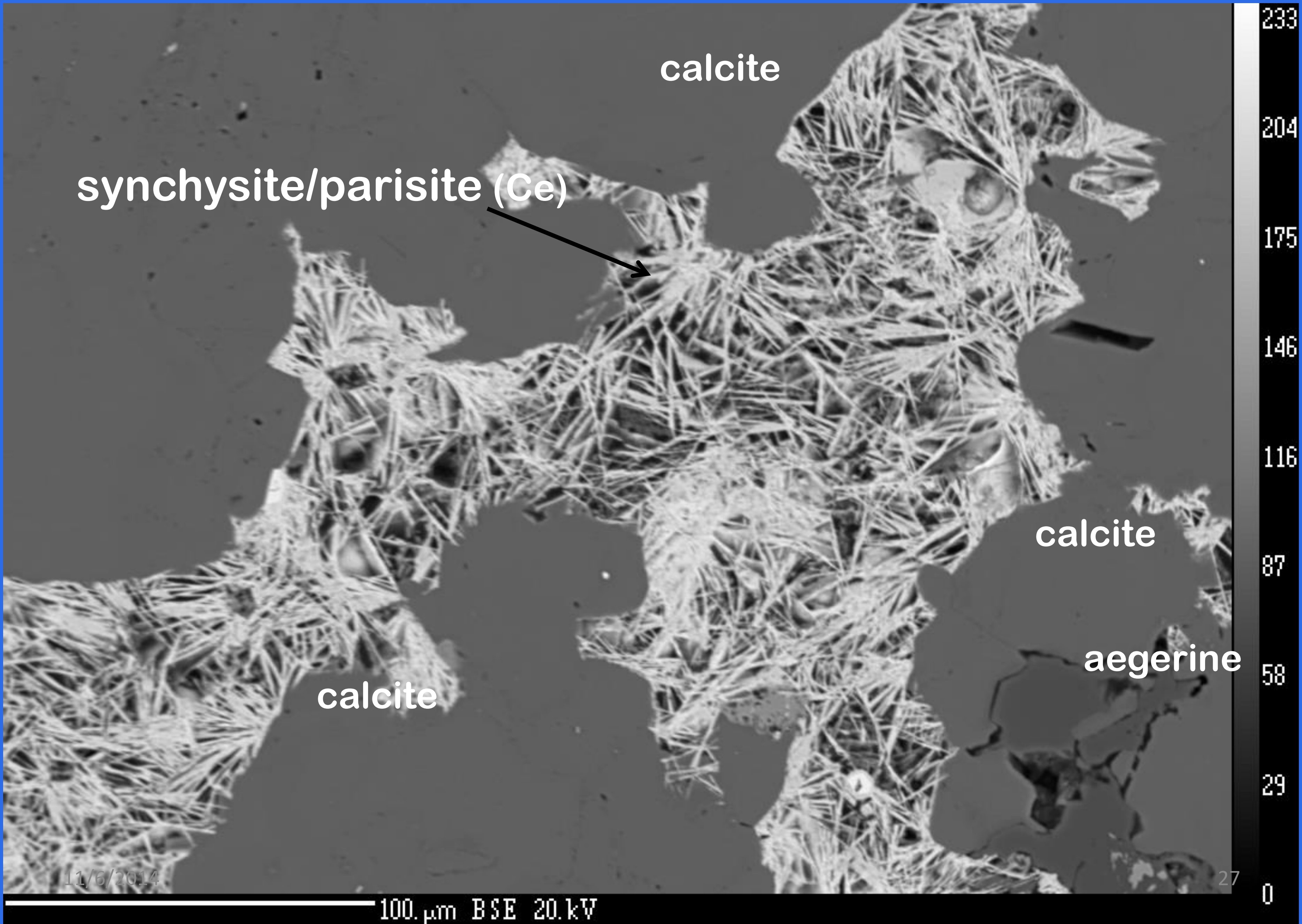
Geochemical classification of the Lofdal carbonatites (using of MgO, CaO and $(FeO+Fe_2O_3+MnO)$

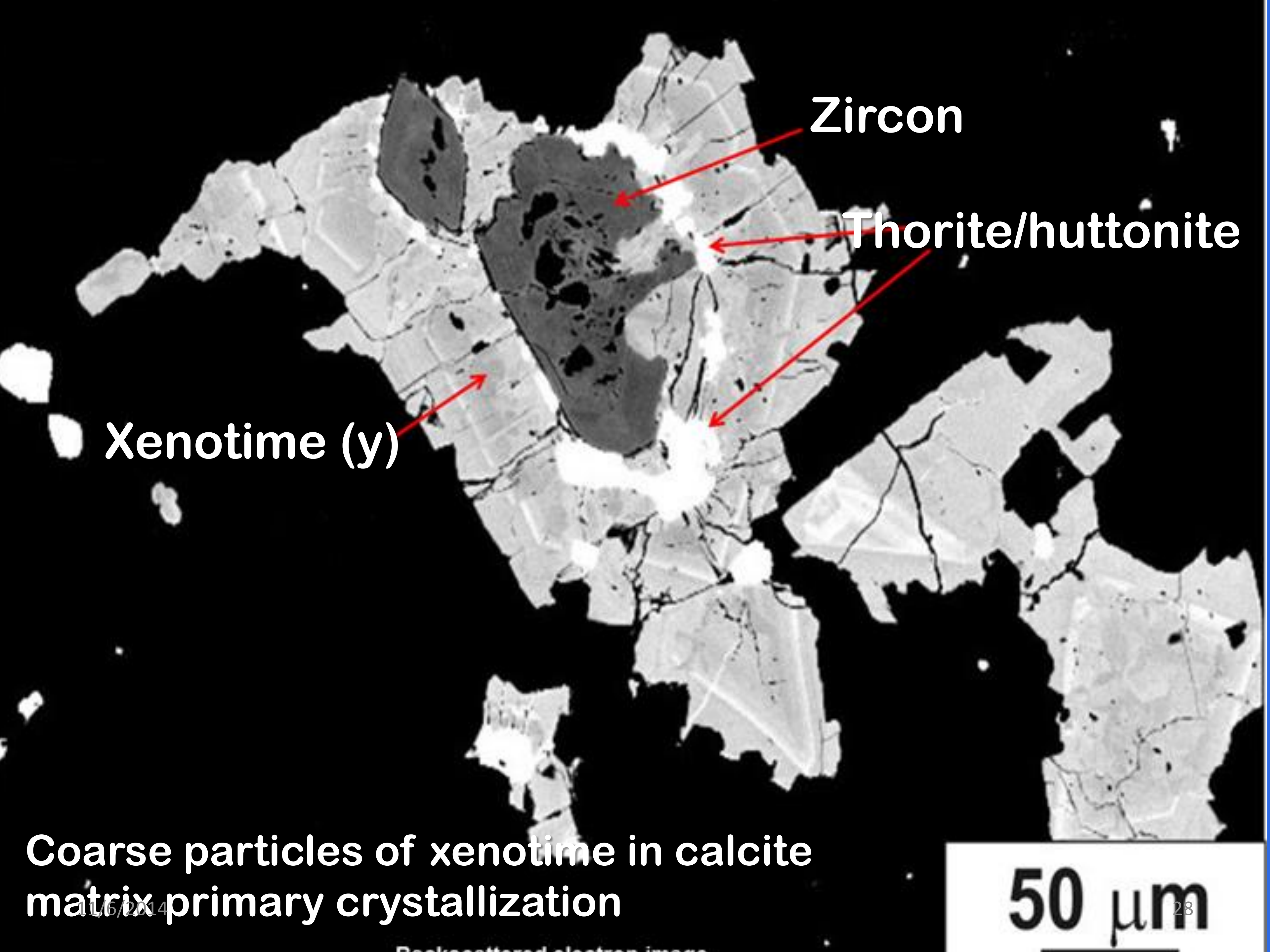


5. Mineralogy of the Lofdal carbonatites

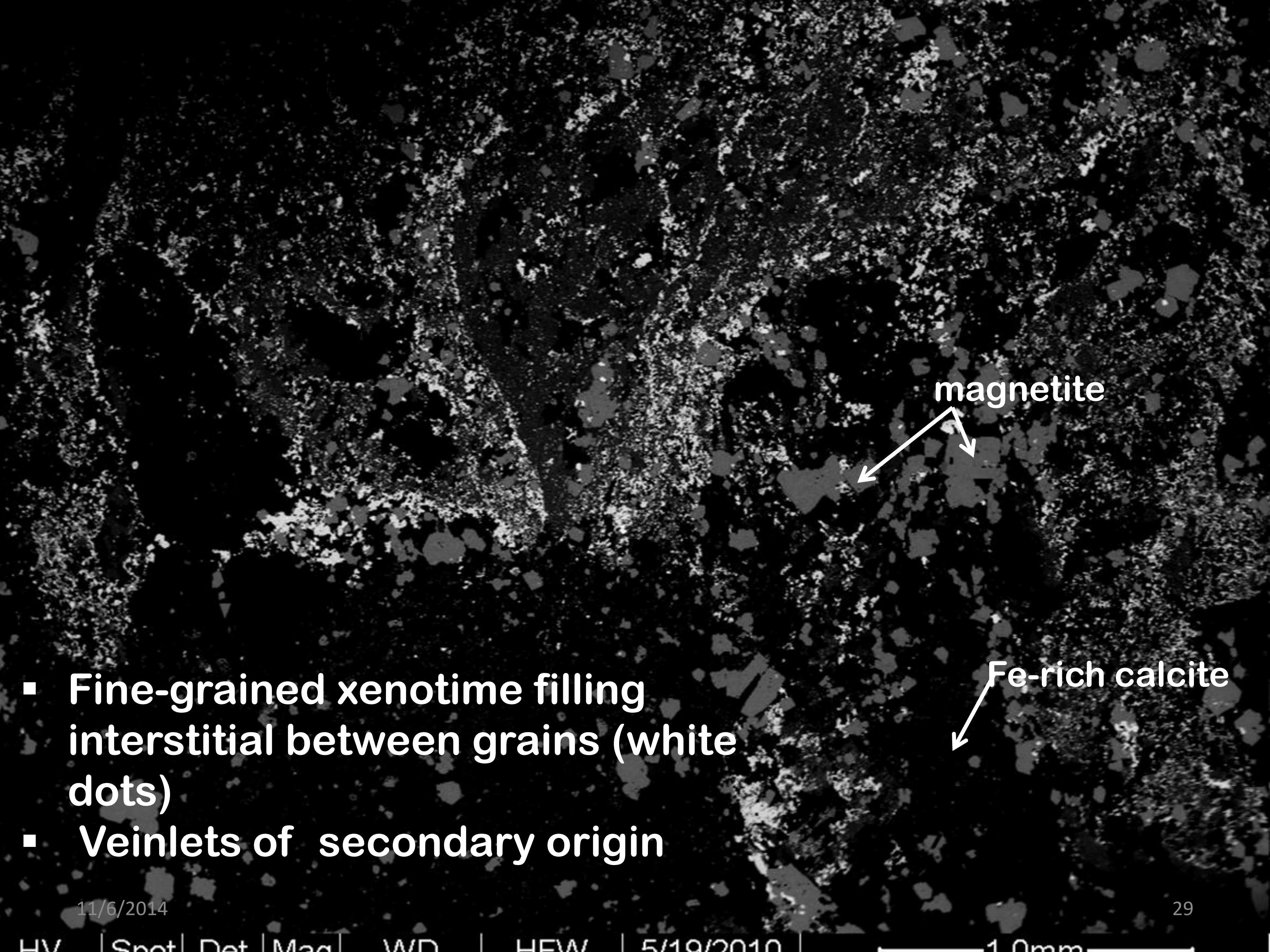
Mineral class	Mineral	Chemical formula
Phosphates	monazite-(Ce)	(Ce, La, Th, Nd, Y)PO_4
	xenotime-(Y)	YPO_4
	apatite	$Ca_5(PO_4)_3F$ (REE observed under CL)
Carbonates	ancylite-(Ce)	Ce, Sr, Ca)$(CO_3)(OH,H_2O)$
	synchysite -(Ce)	Ca(Ce, La)$(CO_3)_2F$
	parisite-(Ce)	Ca(Ce, La)$_2(CO_3)_3F_2$
	carbocernite, -(Ce)	(Ca, Na)(Sr, Ce, Ba)$(CO_3)_2$
Oxides	cerianite -(Ce)	(Ce,ThO_2
	pyrochlore	(Na, REE, K,U)$_2$ (Nb, Ta, Ti)$_2$ (O,OH,F)
Silicates	allanite-(Ce)	{Ca, Ce}{Al $_2Fe^{+2}$}$(Si_2O_7)(SiO_4)O(OH)$
	zircon	(Zr, REE) SiO_4
Halides	fluorite	(Ca, REE) F (REE observed under CL

BSE indicating LREE-fluoro-carbonates from the main carbonatite plug



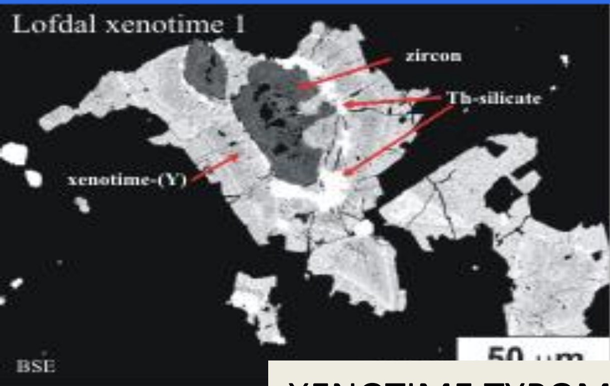


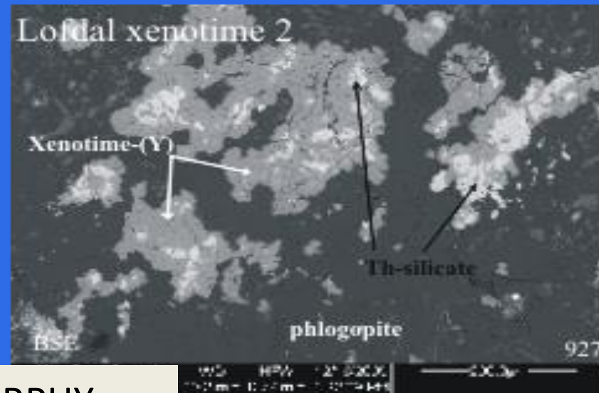
Coarse particles of xenotime in calcite matrix primary crystallization

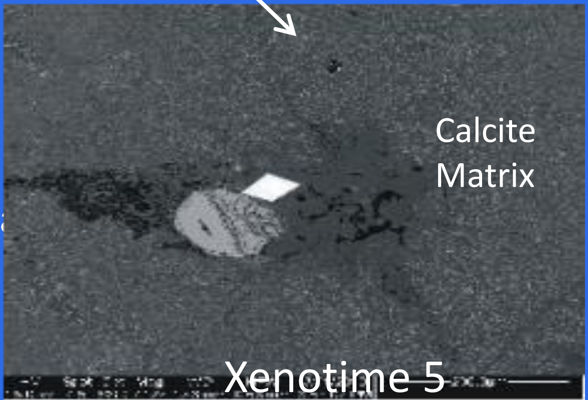


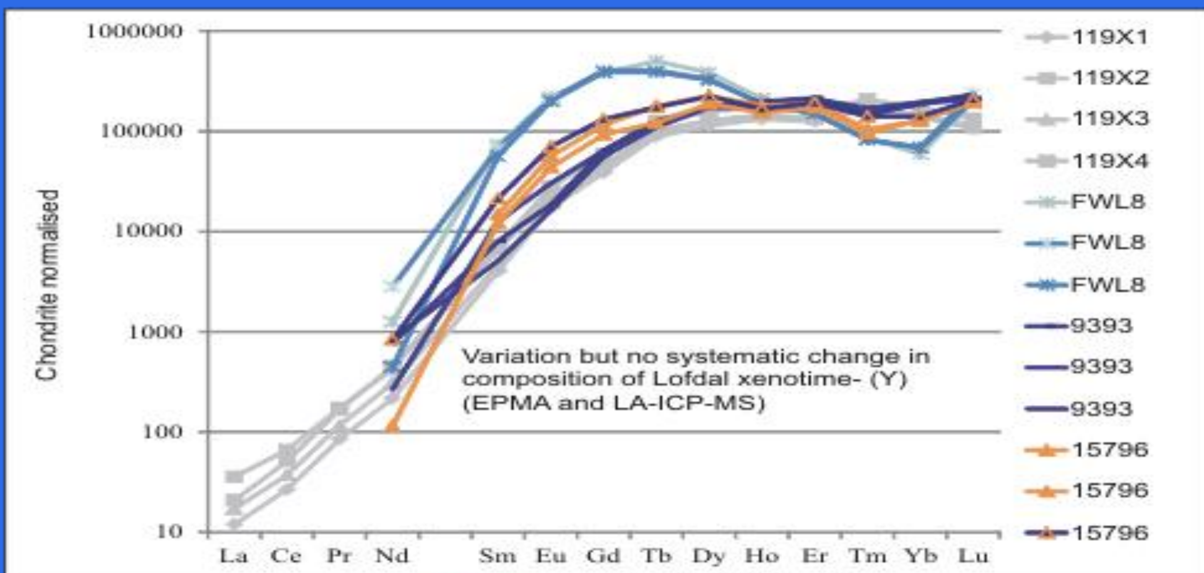
- Fine-grained xenotime filling interstitial between grains (white dots)
- Veinlets of secondary origin

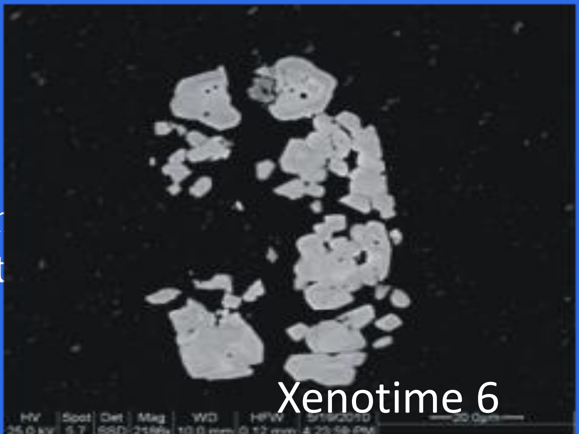
XENOTIME TYPOMORPHY

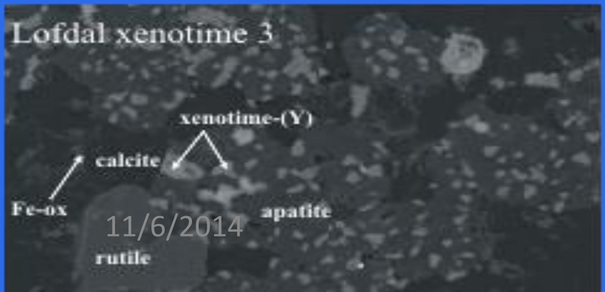






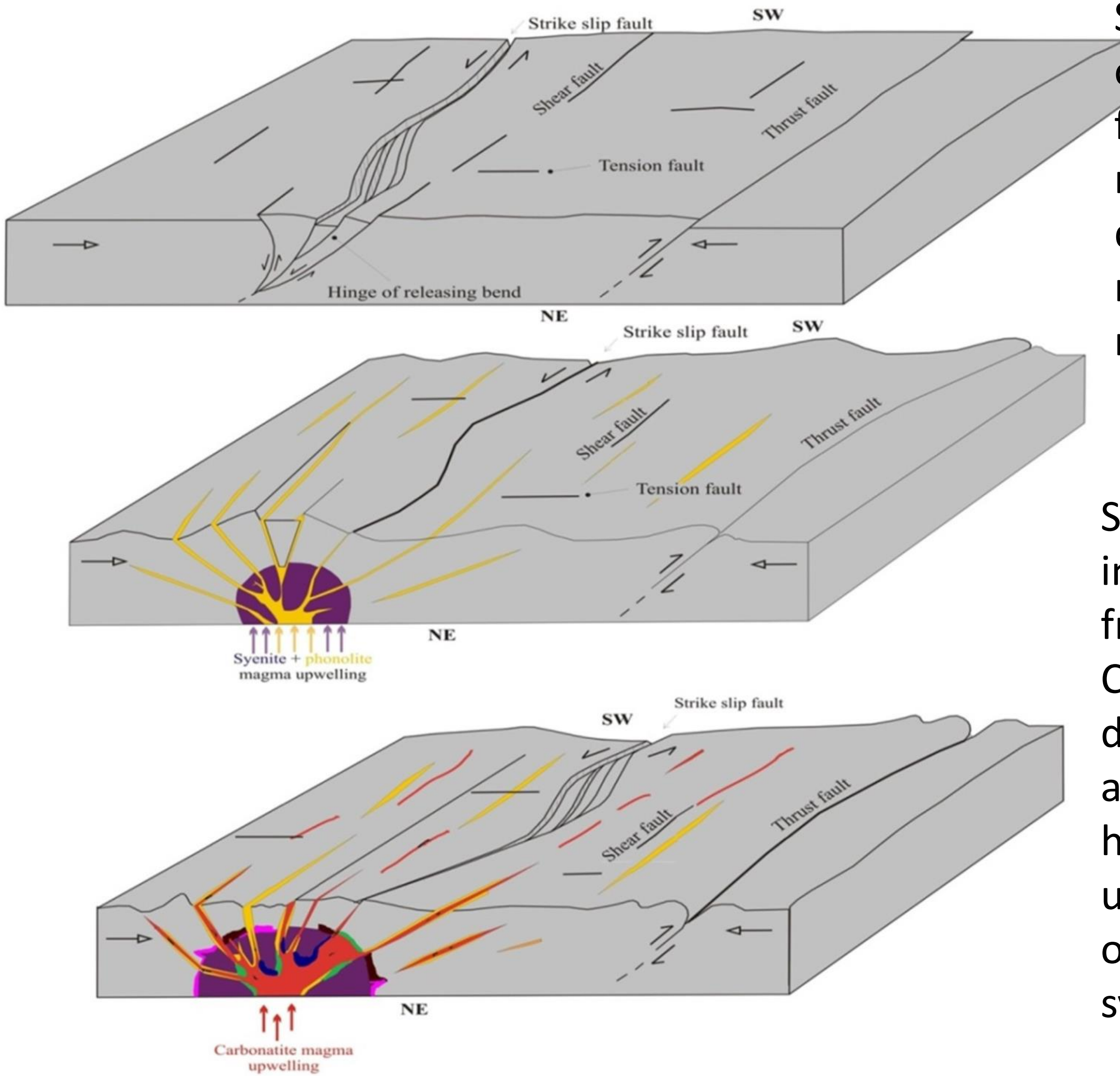






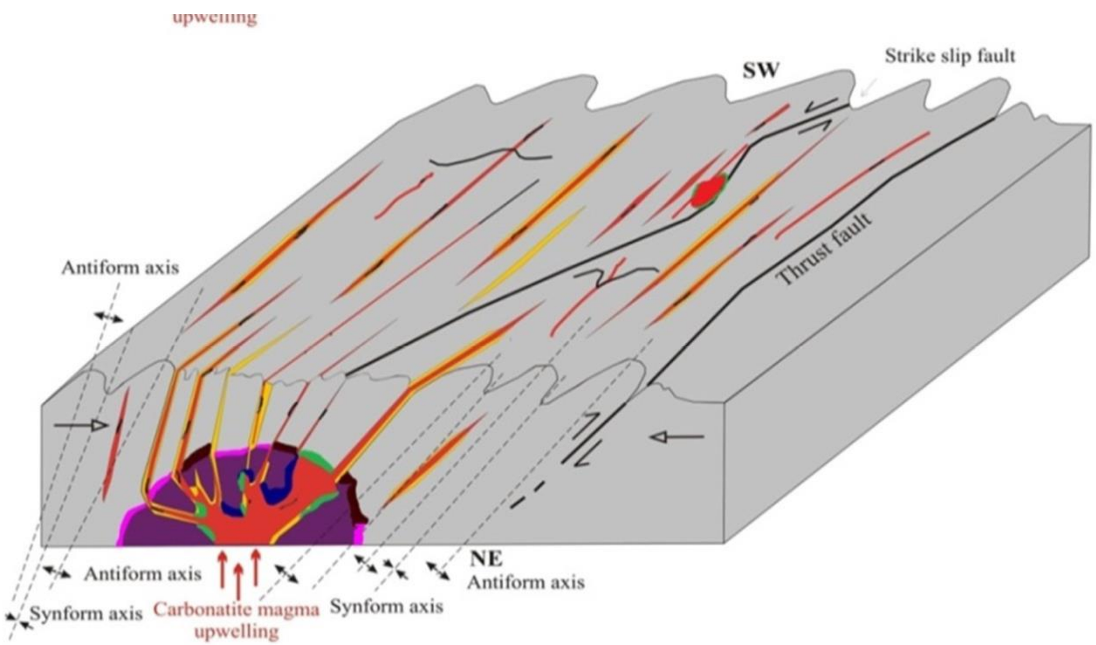
LREE

6. Genesis of the Lofdal carbonatites and their REE mineralisation

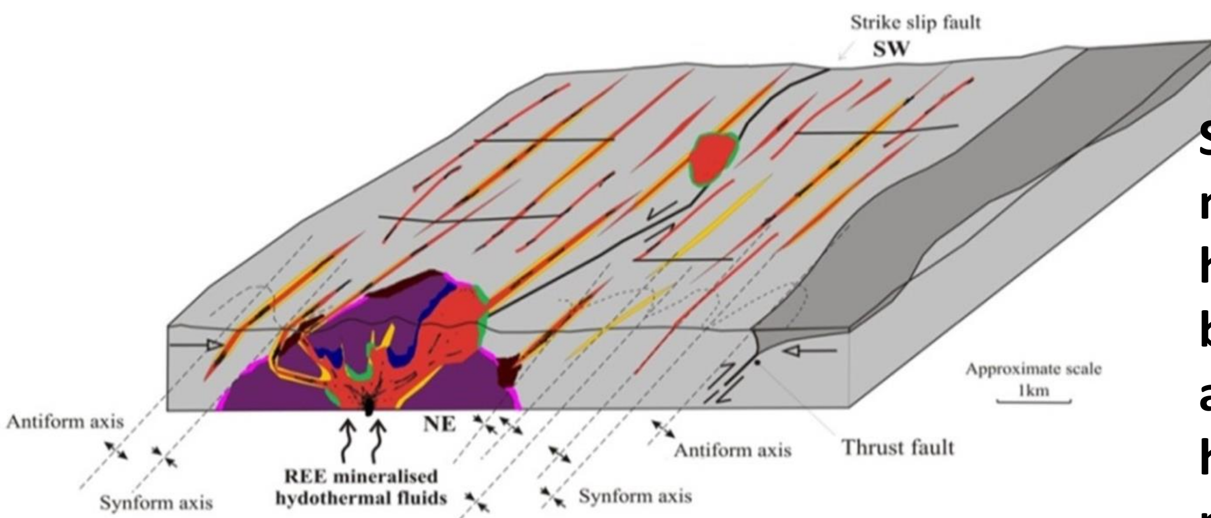


Schematic illustrations of thrusting and faulting developed in response to the strain developed during the rifting and extensional regime.

Syenites and phonolites intrusion along regional fracture systems. Carbonatites plugs and dykes intrude accompanied by hydrothermal fluids utilising the same conduit of dilation fracture systems.

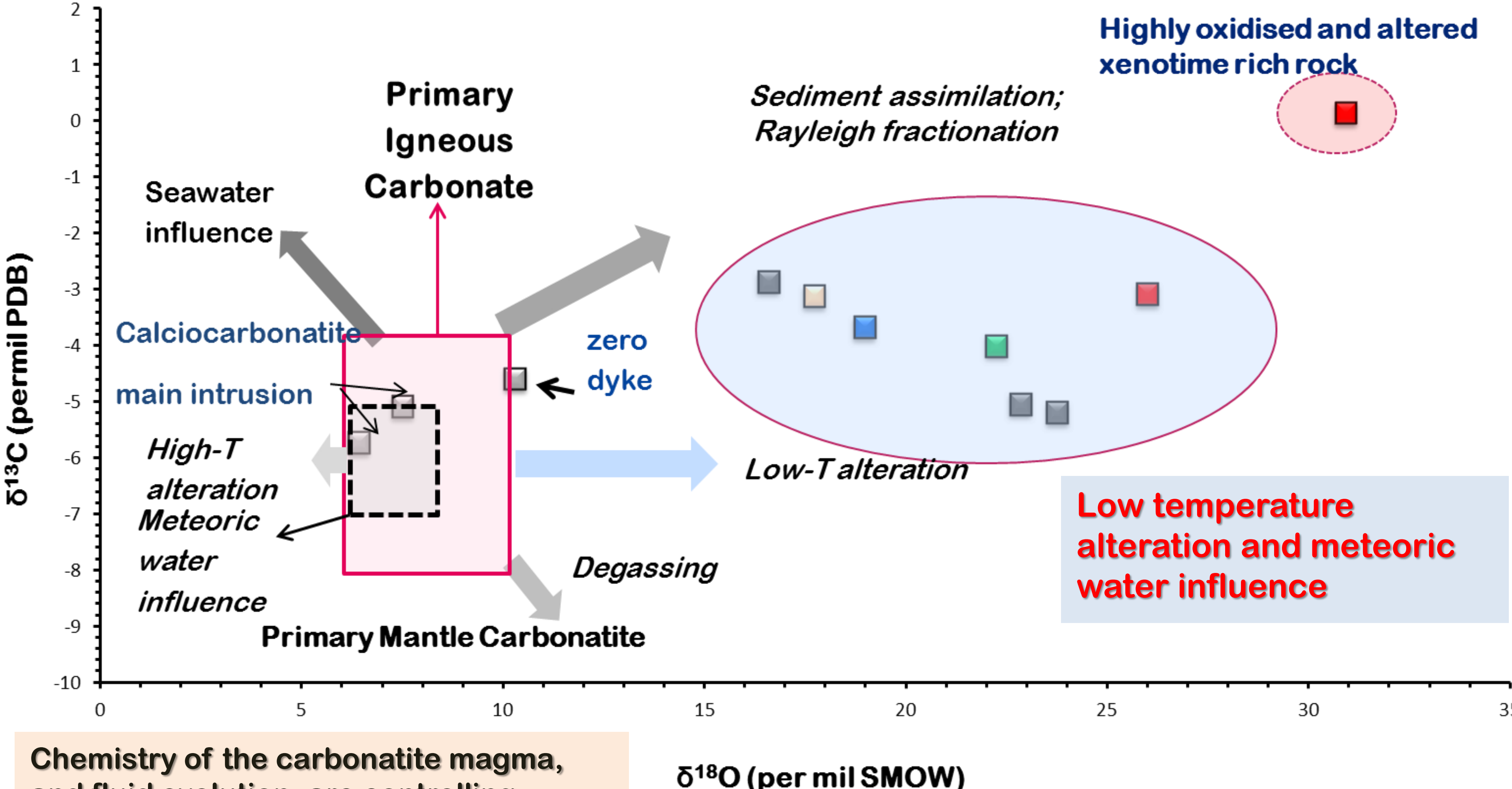


Release bend and or stepover feature formed along the sinistral strike slip zone, producing a duplex structure, allowing alkaline and carbonatite magmas passage through the two echelons left lateral strike slip fault into country rock.



Syenites and carbonatites magma intruded into the hinge zone of the pull-apart basin. The carbonatite dykes are later REE mineralised by hydrothermal fluids– presumably car-bonatite-derived

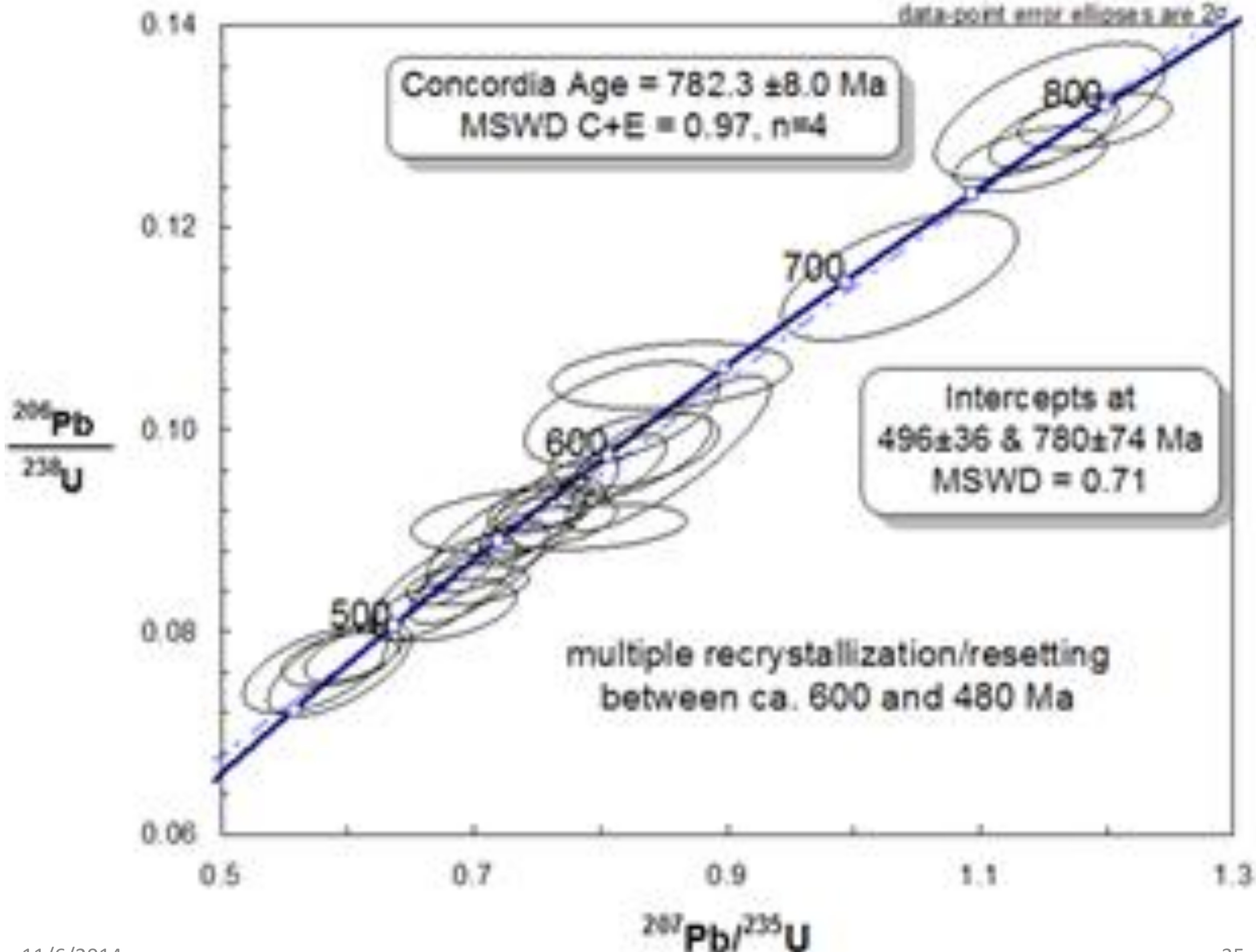
$\delta^{18}O-CO_3$ (‰ SMOW) vs $\delta^{13}C-CO_3$ (‰ PDB)



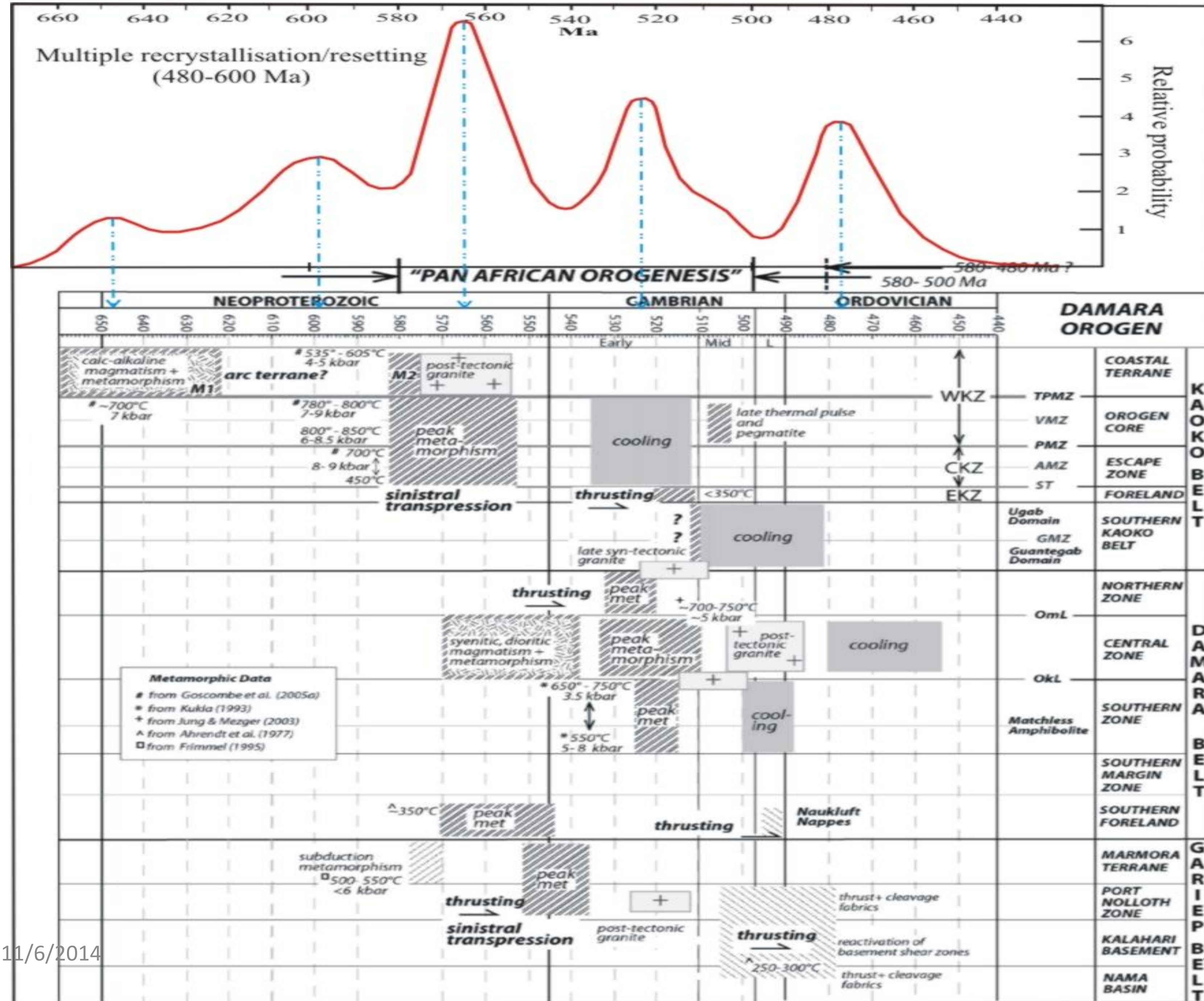
Chemistry of the carbonatite magma, and fluid evolution, are controlling factors for HREE mineralisation

Data analysed by BGR (2010) for the purpose of this research work

After Taylor et al. (1967)
initial carbonatite isotope composition range from $\delta^{18}0$ (6.0 to 8.5$\%_0$) and $\delta^{13}C$ (-5.1 to -7.3$\%_0$)



data-point error ellipses are 2σ
Concordia Age = 782.3 ±8.0 Ma
MSWD C+E = 0.97, n=4
800
700
600
500
Intercepts at
496±36 & 780±74 Ma
MSWD = 0.71
multiple recrystallization/resetting
between ca. 600 and 480 Ma
0.14
0.12
0.10
0.08
0.06
0.5
0.7
0.9
1.1
1.3
206Pb/238U
207Pb/235U



Multiple recrystallisation/resetting (480-600 Ma)
Ma
Relative probability
"PAN AFRICAN OROGENESIS"
580-480 Ma ?
580- 500 Ma
NEOPROTEROZOIC
CAMBRIAN
ORDOVICIAN
DAMARA OROGEN
Early
Mid
L
calc-alkaline magmatism + metamorphism
M1
arc terrane?
M2
post-tectonic granite
COASTAL TERRANE
WKZ
TPMZ
VMZ
OROGEN CORE
PMZ
CKZ
AMZ
ESCAPE ZONE
ST
EKZ
FORELAND
KAOKO BELT
peak meta-morphism
cooling
late thermal pulse and pegmatite
sinistral transpression
thrusting
late syn-tectonic granite
Ugab Domain
GMZ
Guantegab Domain
SOUTHERN KAOKO BELT
NORTHERN ZONE
OmL
syenitic, dioritic magmatism + metamorphism
post-tectonic granite
CENTRAL ZONE
OkL
Metamorphic Data
from Goscombe et al. (2005a)
from Kukla (1993)
from Jung & Mezger (2003)
from Ahrendt et al. (1977)
from Frimmel (1995)
peak met
Matchless Amphibolite
SOUTHERN ZONE
SOUTHERN MARGIN ZONE
Naukluft Nappes
SOUTHERN FORELAND
DAMARA BELT
subduction metamorphism
MARMORA TERRANE
thrust + cleavage fabrics
PORT NOLLOTH ZONE
reactivation of basement shear zones
KALAHARI BASEMENT
NAMA BASIN
GARIEP BELT

7. Comparison with Worldwide Calciocarbonatites and REE-rich deposits

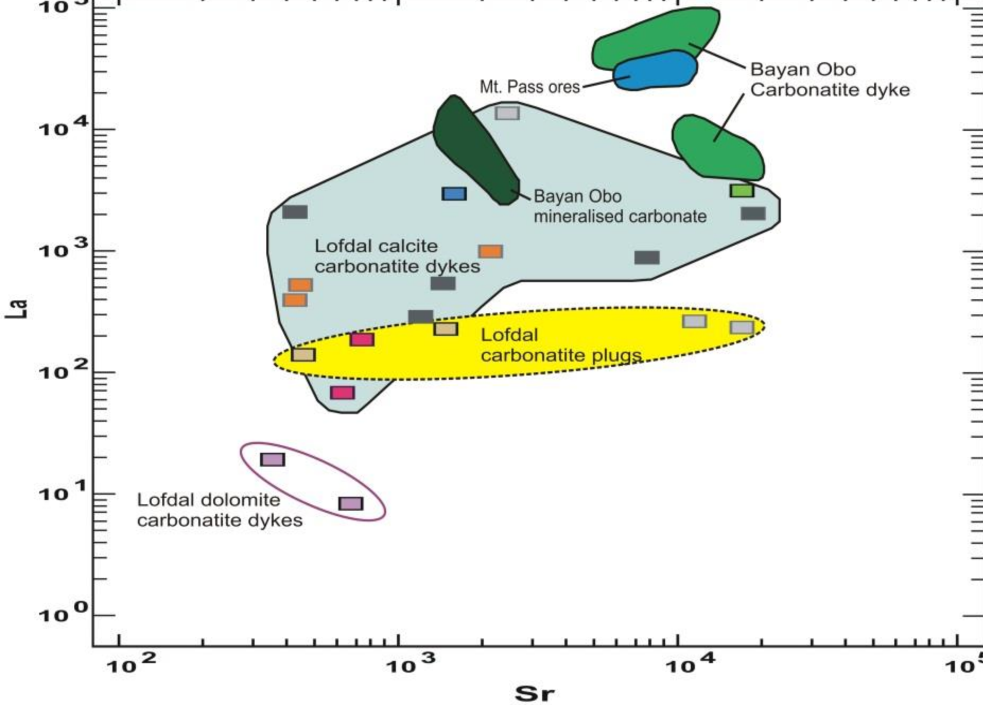
	Av Ca- carb	Min – max	av Ca -Carb (Main plug and Zero)	Min-max	ave	Min - Max	ave	Min-max	ave	Min - Max	average	Min - Max	NAM - 914	NAM - 924
La	608	90 - 1600	845	238-2032	938	141 - 2089	1377	287-3126	663	394 - 998	129	68.2 - 190	13850	2952
Ce	1687	74 - 4152	1481	442-3488	1490	234 - 3312	2073	548 - 4462	1098	719 - 1562	270	198 - 341	26334	4458
Pr	219	50 - 389	150	44.9-351	136	25 - 299	184	56 - 376	120	89 - 161	34	30 - 38	2612	420
Nd	883	190 - 1550	485	150-1133	409	79 - 892	531	185 - 1027	483	404 - 594	155	152 - 158	8305	1362
TLREE	3397	219 -6691	3352	875-7004	2973	478 - 6592	4165	1076 - 8991	2367	1622 - 3315	588	448 - 727	51101	9192
Sm	130	95 - 164	63	22-143	39.3	11 – 79	56	28 - 91	496	455 - 536	178	128 - 227	908	280
Eu	39	29 - 48	17	6-38	10.1	4 -19	13	8 - 18	186	139 - 230	87	71.3 - 102	194	123
Gd	105	91 - 119	46	16-103	24.4	9 - 43	38	22.5 - 55.9	442	237 - 602	289	286 - 291	461	419
TMREE	274	29 - 164	141	45-28387	73.7	24 -140	107	59.4 - 165.2	1132	874 - 1367	553	485 - 620	1563	822
Tb			7	2-16	3.33	1 -5	6	3.13 - 9.04	50.7	17 - 73	50	41 - 59.6	41.7	60.8
Dy	34	22 - 46	45	12-107	19.5	10 - 27	36	17.2 - 67.1	225	59 - 359	267	180 - 353	160	278
Y	119	25 - 346	258	60-642	98	50 - 130	231	87.6 - 473	789	216 - 1325	1210	584 - 1835	742	1276
Ho	6	3 -9	10	2-23	4	2 - 5	8	3.32 - 16.3	32.8	8 - 55	45	25 - 66	22.9	42.6
Er			29	6-72	14	8 - 19	26	9.6 - 56.4	78.3	21 - 134	116	56.8 - 175	52.1	109
Tm			4	1-11	3	2 - 4	4	1.4 - 9.12	10.2	3 - 17	16	6.81 - 25.2	5.82	14.6
Yb	5	1.5 - 12	28	5-70	21.9	15 - 29	28	9.33 - 61.3	59.9	17 - 103	100	38.3 - 161	32.6	95.1
Lu	1		4	1-9	3.64	3 - 5	4	1.34 - 8.26	7.98	2 - 14	14	4.68 - 23.4	4.57	12.7
THREE	164.7	0 -346	384	90-951	167	91 - 224	343	132.92 - 700.52	1253	344 - 2079	1817	937.19 - 2697.8	1061.69	1888.8
TREE	3835.7	918 - 10632	3931	1009-8238	3211	593 - 6944	4628	1346.68 - 9856.72	4621	2840 - 6102	3182	2284 - 3631.4	53725.69	11902.8

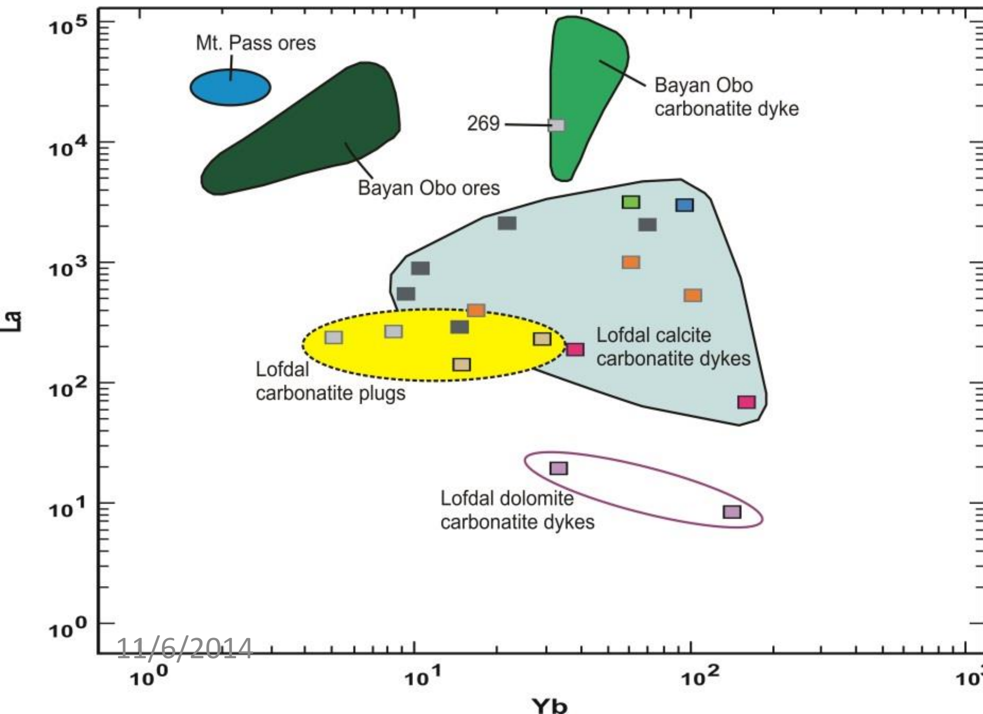
Pink	Exceed limit
Green	Within carbonatite average and Min-Max
Orange	below average and Min-Max
Dark pink	Far above averageand Min-Max
Light green	Far Below average and Min-Max

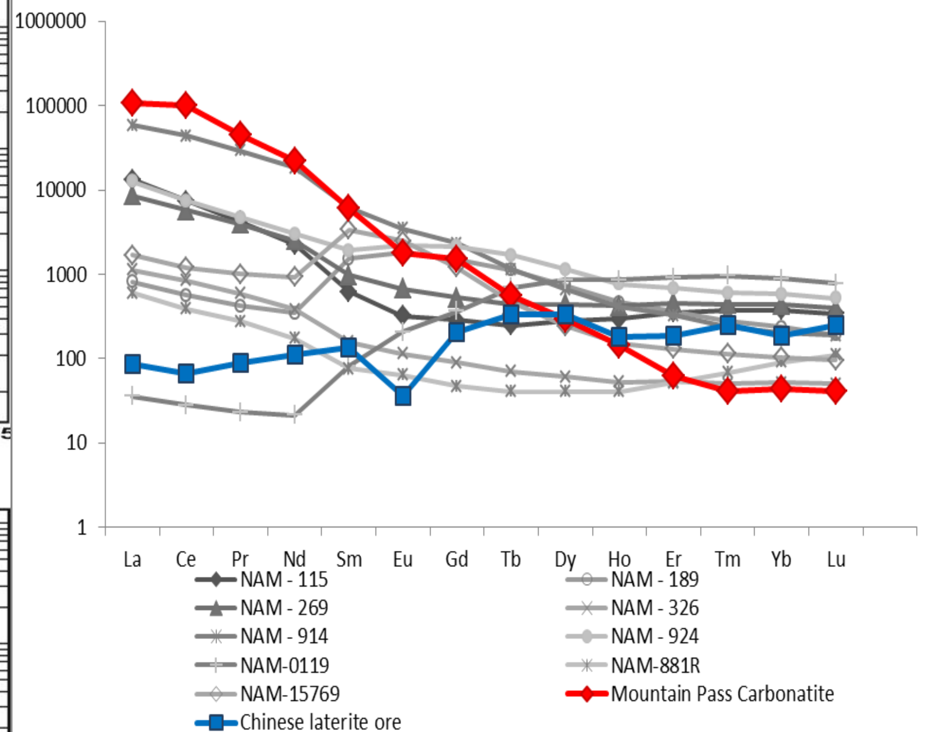
Comparison with average calcio carbonatite by Woolley and Kempe (1989)

- unusually low LREE: HREE ratio in Lofdal carbonatite dykes
- MREE and HREE very high for the Lofdal carbonatite dykes

Comparison of Lofdal carbonatites with other known REE –RICH carbonatites







- The overall conclusion are:
- REE deposits are specific
- REE distributions at Lofdal are variable

Resources available:

At a 0.3% total REE cut-off:

- Indicated resource: 900 000 t @ 0.62% total REE, with 86% heavy REE
- Inferred resource: 750 000 t @ 0.56% total REE, with 85% heavy REE

At a 0.1 total REE cut-off:

- Indicated resource: 2.88 million t @ 0.32% total REE, with 76% heavy REE
- Inferred resource: 3.28 million t @ 0.27% total REE, with 75% heavy REE

The results of the Ph.D. study supported the development of this potential future Namibian mine, and thereby contributed to economic development in an otherwise underdeveloped area.

Mineralisation at Lofdal

- **Lofdal is 1 to 3 times higher than the maximum values in the Le Bas data set and 2 to 8.9 Le Bas standard median values.**
- **At Lofdal principal REE occur in minerals xenotime, thorite/hutonite, monazite, bastnaesite, parisite, allanite, calcite and apatite,**
- **The REE-rich minerals are disseminated throughout the carbonatite dykes and fracture zones in the country rock but associated with carbonate materials**

How to find another Lofdal ?

Geophysical criteria

- Radiometric
- Hyperspectral RS

Structural criteria

- Structure controlled by the faulting and shearing process that allow infiltration metasomatism type of fluid
- Elements of rifting and extensional regime.
- Chain of alkaline intrusions

Above all the source of fluids is most important

8. Conclusion

1. The LAC consist of a swarm of carbonatite dykes and plugs, with spatially associated silicate intrusive rocks
2. Carbonatites are classified as calciocarbonatites, magnesiocarbonatites, ferruginous carbonatites and dolomites and are grouped into eight (8) main groups according to their geochemistry
3. Lofdal is unique in HREE enrichment hosted by xenotime-(Y), thorite, zircon, apatite and fluorite while LREE are hosted by pyrochlore, parisite-Ce), synchysite-(Ce) and monazite-(Ce)
4. The $\delta^{l8}O$ and $\delta^{13}C$ isotopic compositions indicate mantle source for the least altered carbonatites and crustal influence for the altered carbonatite dykes. Highly altered carbonatite dykes show influence by secondary processes involving meteoric water
5. HREE mineralization at Lofdal is directly related to the emplacement of the carbonatite and to a post-magmatic hydrothermal process
6. The age of intrusion of Lofdal is ± 765

Thank you