How technology has evolved in the last 50 years and its impact on Iron Ore

presented by:
Armando Corrêa de Araujo
Principal Scientist Mining – ArcelorMittal Global R&D

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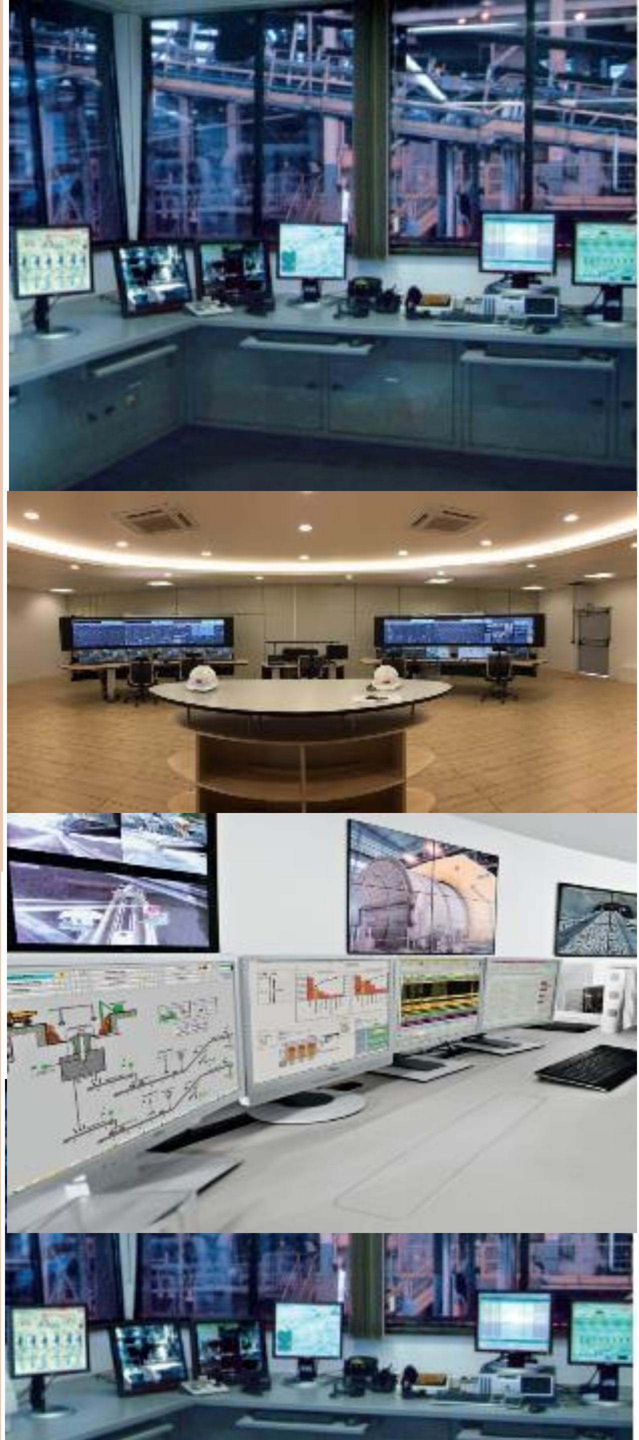
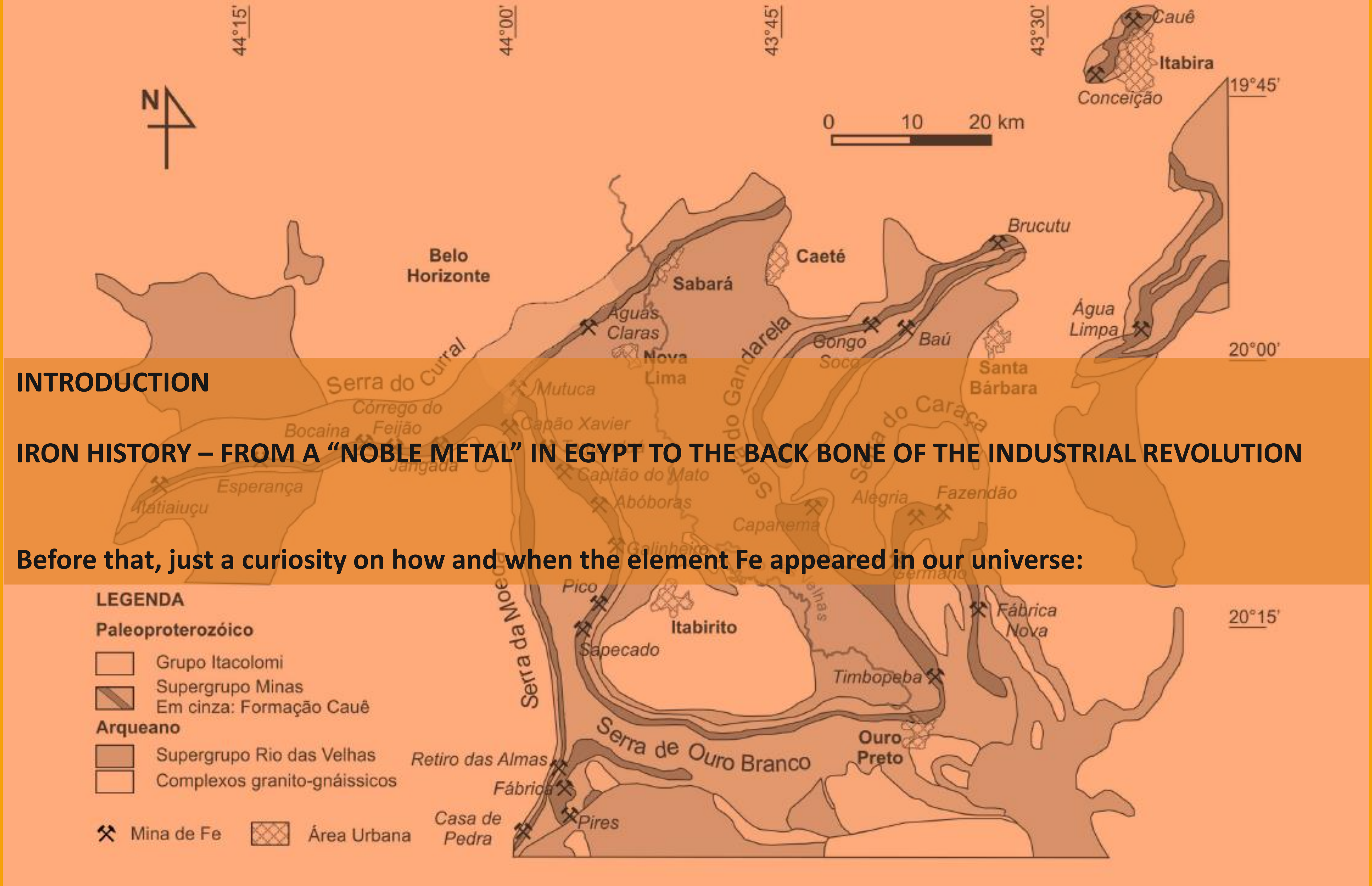
1987
2013
AURORA

Table of Contents

1. Introduction
2. Iron ores: 50 years of (re)evolution
3. Major technological changes in:
   - Comminution
   - Size Separation
   - Solid-solid separation
     - Magnetic Methods
     - Gravity Methods
     - Flotation
     - Sorting and others
   - Solid-liquid separation
     - Thickening
     - Filtration and Centrifugation
     - Tailings disposal
4. Concluding remarks

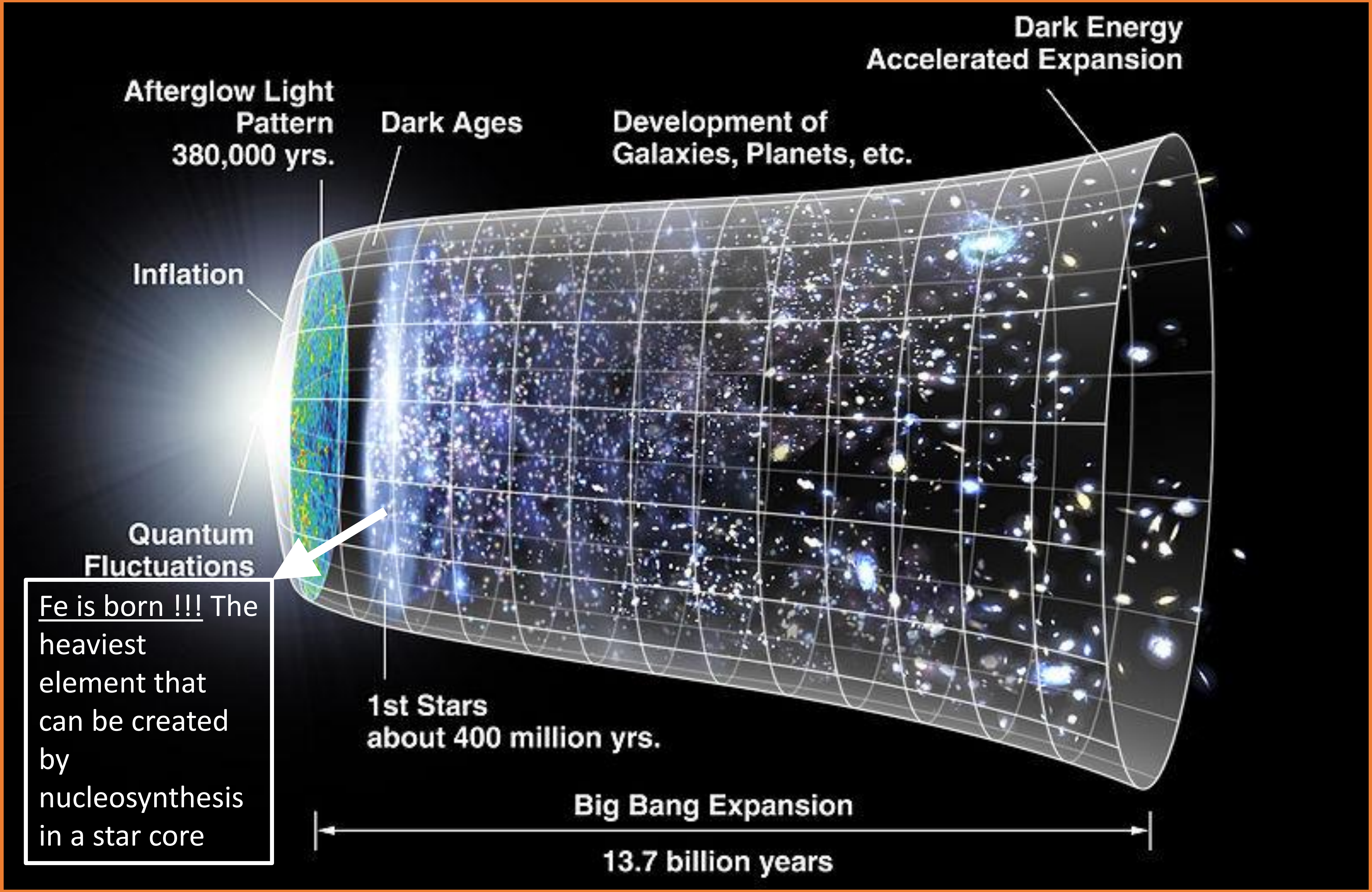




INTRODUCTION

IRON HISTORY – FROM A “NOBLE METAL” IN EGYPT TO THE BACK BONE OF THE INDUSTRIAL REVOLUTION

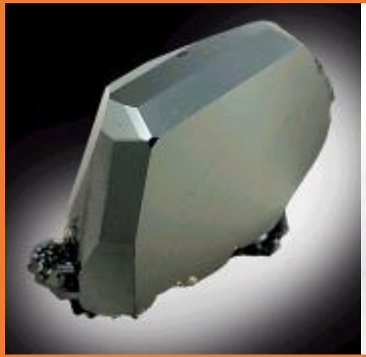
Before that, just a curiosity on how and when the element Fe appeared in our universe:



<u>Fe is born !!!</u> The heaviest element that can be created by nucleosynthesis in a star core

On the crust of our planet we can count **1260** different minerals that contain iron in their structures but only 4 (0.32%) are relevant to the steel industry, namely:

HEMATITE
MAGNETITE
GOETHITE
SIDERITE




Iron in Ancient Egypt (prior to Iron Age)

Iron was a metal of mythical character. For thousands of years before they learned to smelt iron ore, Egyptians were crafting beads and trinkets from it, harvesting the metal from fallen meteorites (3500-500 BC).

"In the hieroglyphic language of the ancient Egyptians it was pronounced *ba-en-pet*, meaning either stone or metal of Heaven."

"Iron was very strongly associated with royalty and power"

This ancient Egyptian iron bead dates back to roughly 3300 BC.
Photo: The Open University / The University of Manchester

Industrial Revolution – some iron and steel Milestones

1709 – Iron firstly smelted with coke (Darby)

1779 – First all iron bridge is built

1781 – Steam engine with a rotary action developed by Watt allows the increase in furnace size, boosting production

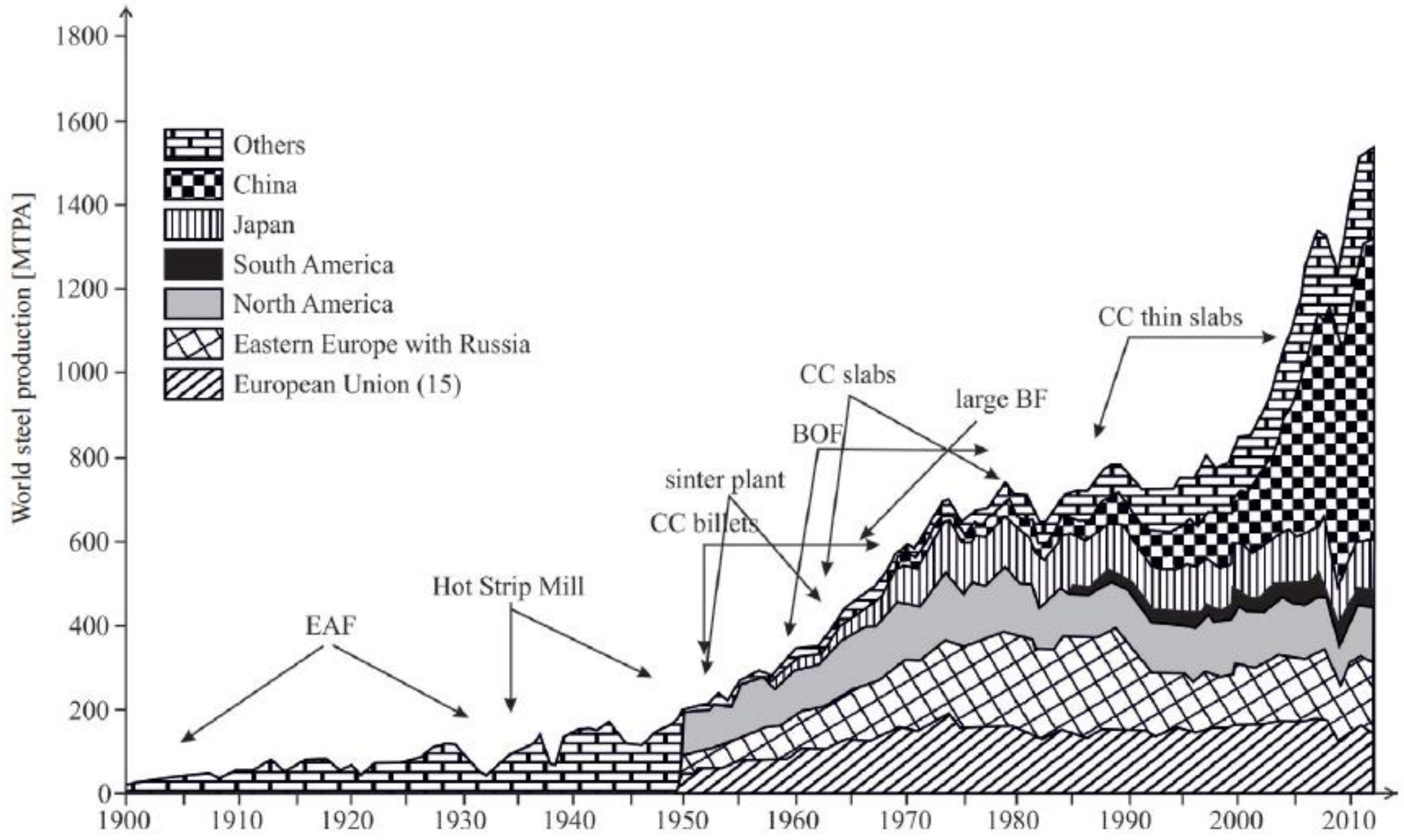
1825 – Start of the NEW IRON AGE (railways, bridges, tunnels, window frames, etc.)

1864 – Bessemer's process went into production reducing the cost of steel by several folds

1890 – Siemens-Martin open hearth furnace, improving quality and further reducing cost of steel

Production figures in Britain

1700 = 12 thousand tonnes/year
1850 = 2 million
1870 = 6.7 million
1913 = 10.4 million



World steel production [MTPA]
1800
1600
1400
1200
1000
800
600
400
200
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Others
China
Japan
South America
North America
Eastern Europe with Russia
European Union (15)
EAF
Hot Strip Mill
CC billets
sinter plant
BOF
CC slabs
large BF
CC thin slabs

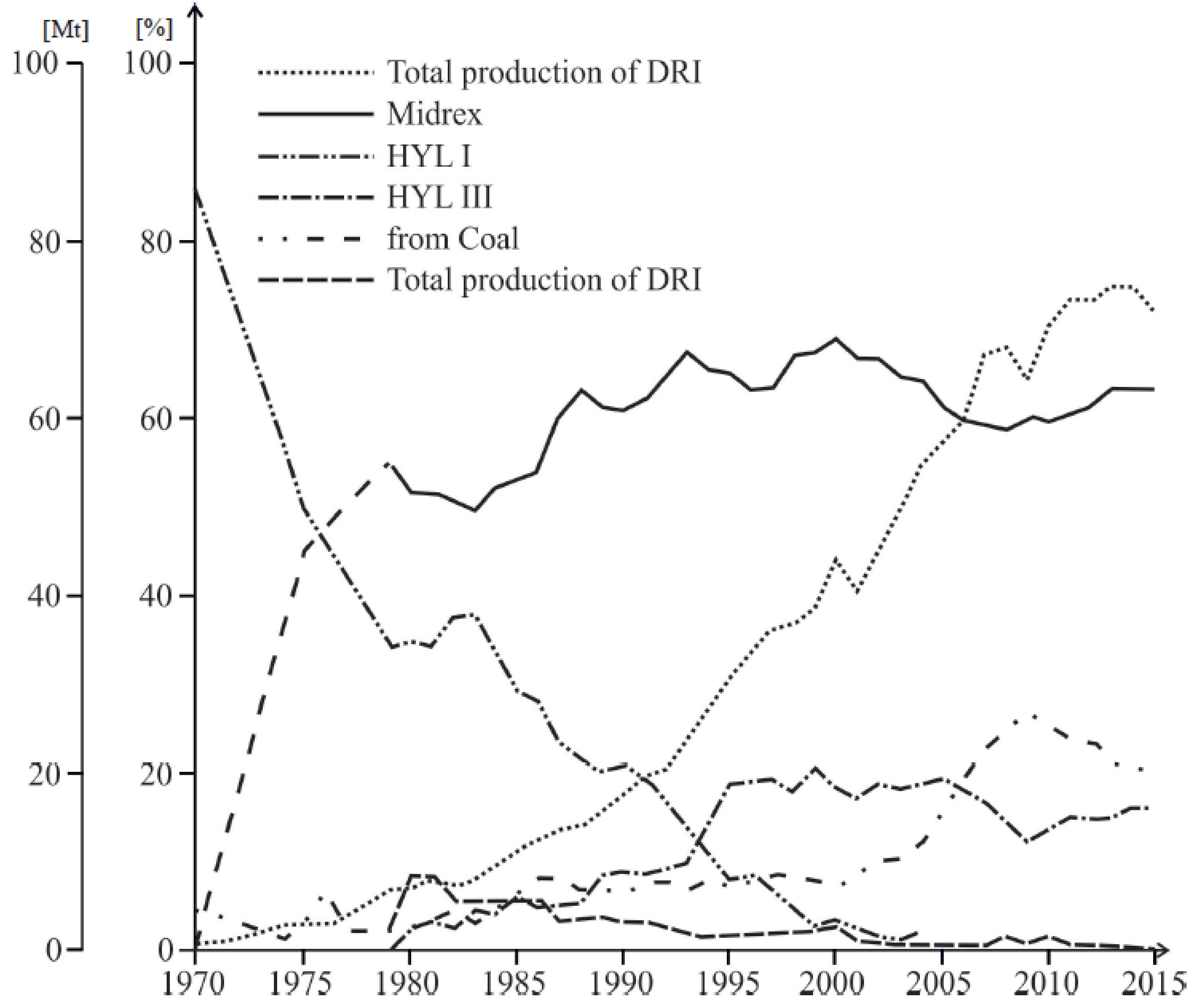
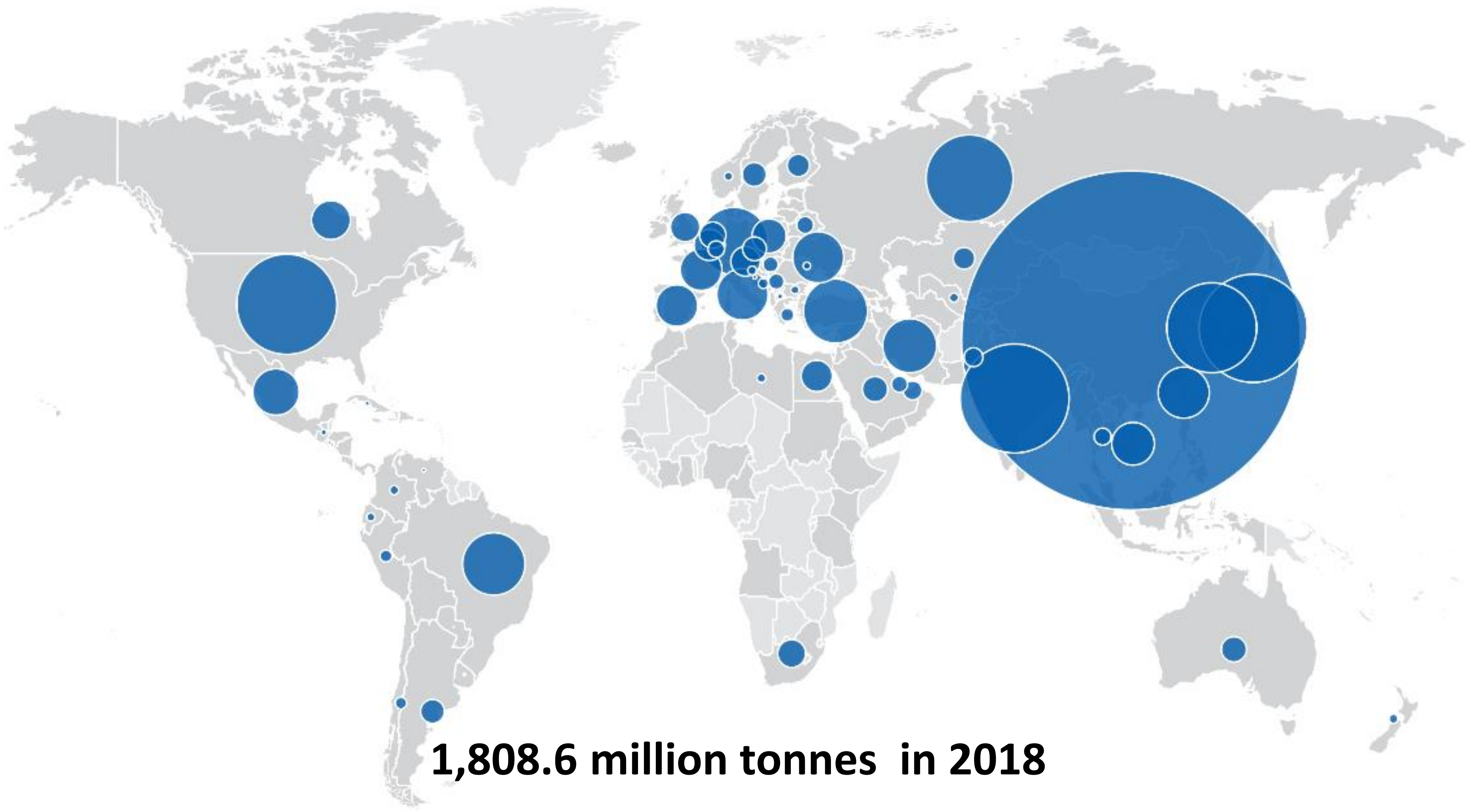


Fig. 19. Evolution of the production of direct reduced iron, by main processes

Apr 2019

Crude steel production monthly (thousand tonnes)



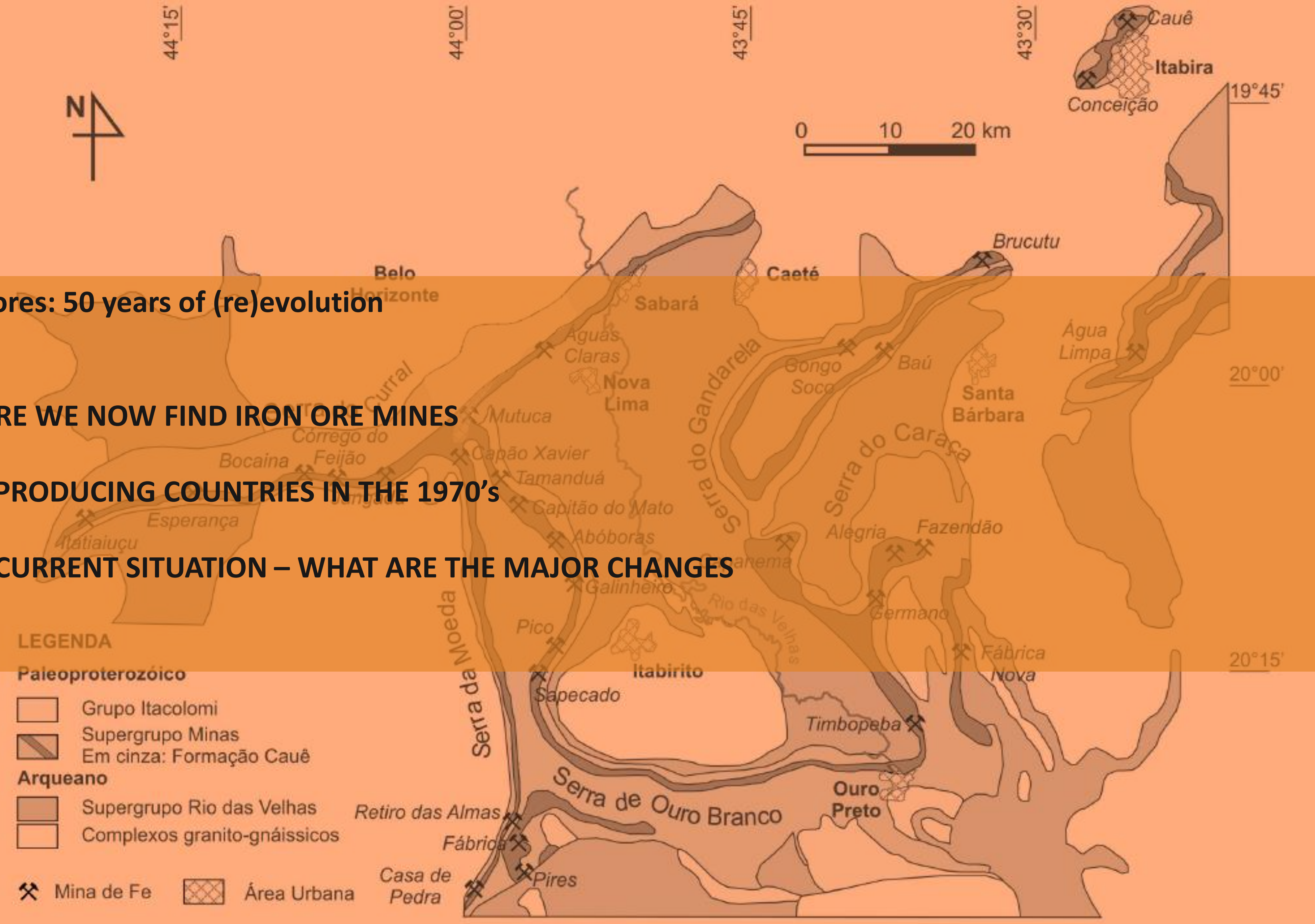
1,808.6 million tonnes in 2018

Iron ores: 50 years of (re)evolution

WHERE WE NOW FIND IRON ORE MINES

PRODUCING COUNTRIES IN THE 1970’s

CURRENT SITUATION – WHAT ARE THE MAJOR CHANGES



Iron ore production in top countries in 1930 (Bednarczuk et al. 1979), 1965 (UN 1970), 2014 (Tuck 2015) and 2015 (WSA 2016).

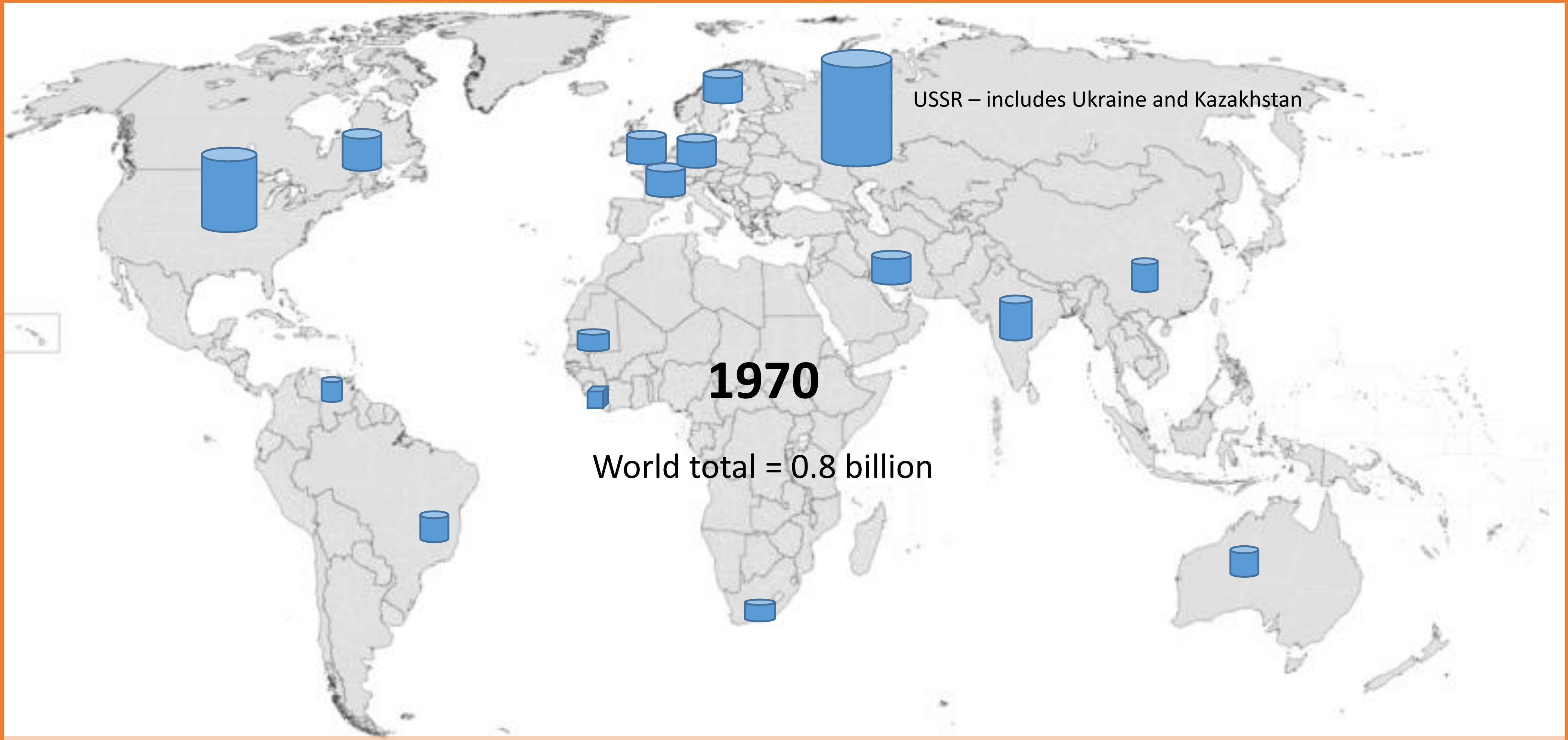
Country	Saleable ore output [Mt]					The world share in 2015 [%]
	1930	1965	2014		2015	
			ore	iron in ore		
Australia	0.95	6.8	774.2	468.0	811.2	40.4
Brazil	0.03	18.2	411.2	262.0	422.5	21.1
India	1.88	23.7	129.1	80.0	142.5	7.1
China	2.25	51.0	1,510.0	193.2	123.5	6.2
Russia	10.15_{USSR}	137.5_{USSR}	102.0	61.7	102.0	5.1
Ukraine			67.9	41.1	82.0	4.1
South Africa	0.05	6.8	37.4	22.6	61.4	3.1
Canada	1.47	36.3	44.2	27.3	46.0	2.3
USA	59.35	88.9	56.1	35.5	43.1	2.1
Iran	–	n.a.	33.0	15.6	39.4	2.0
Sweden	11.24	29.4	37.4	22.6	24.6	1.2
France	48.57	59.5	0	0	0	0
World	179.3	627.1	2,330	1,430	2,006.3	100.0

n.a. – not available.

France: 45000km of tunnels, adits, shafts, etc. Last mine in operation in 1997

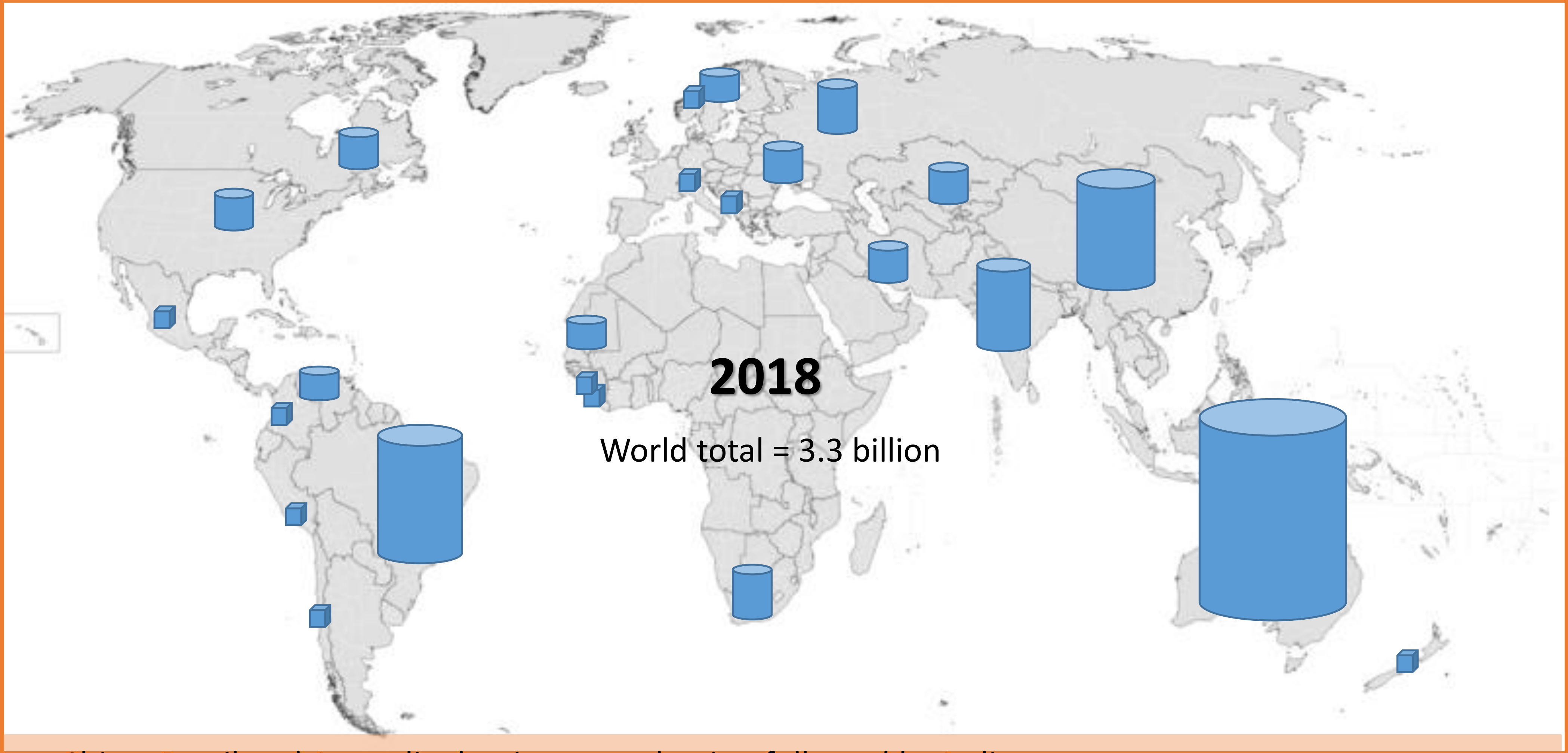
Sweden: The most technologically advanced underground iron ore mine in the world. Kiruna, home town of the largest mine, is being moved to a new location

IRON ORE PRODUCING COUNTRIES



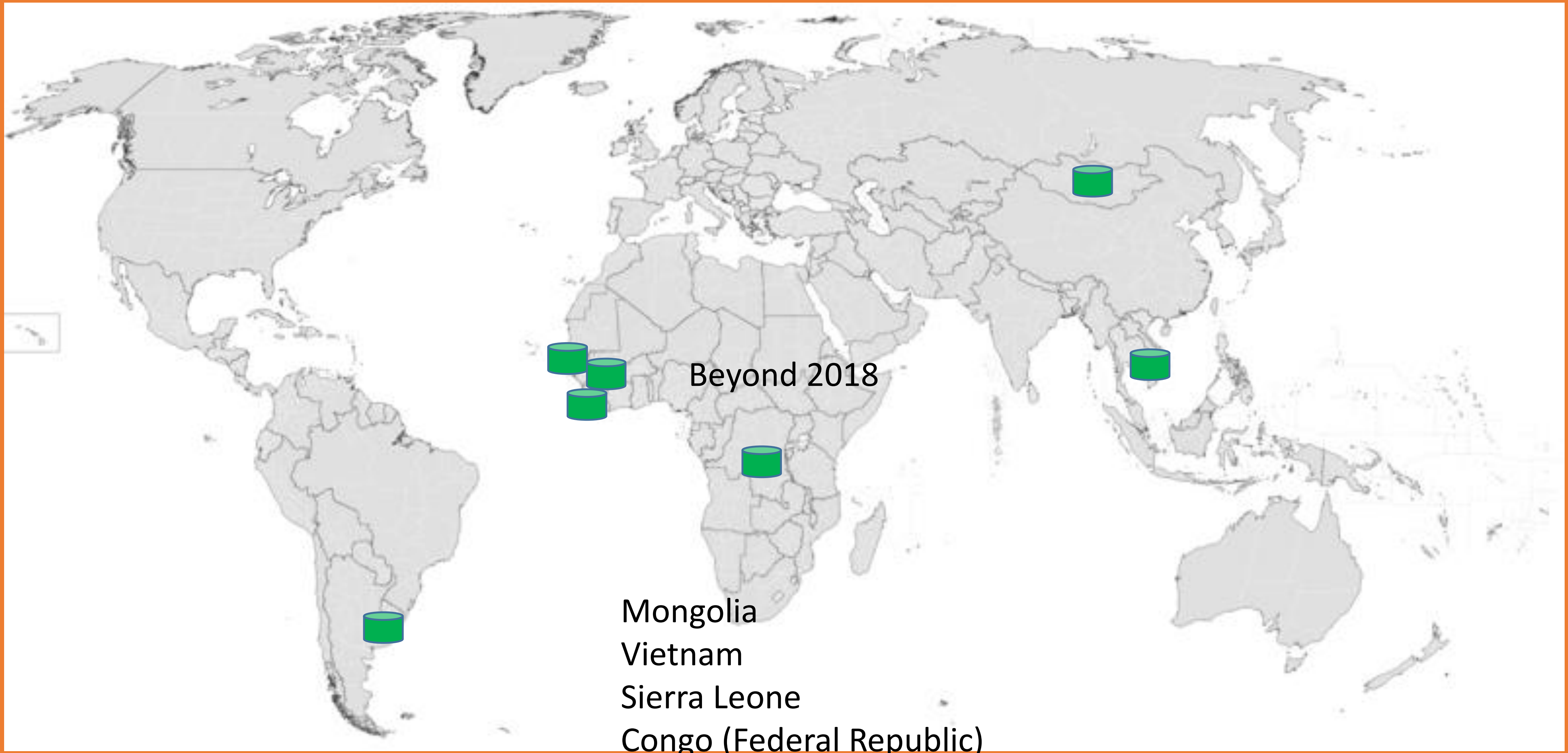
- Significant production took place in Europe; China, Brazil and Australia: NO SIGNIFICANT production
- USSR was the largest single producer followed by the USA
- Some of the main projects under development in Australia and Brazil linked to Japanese traders
- Projects in West Africa linked to European Steel companies

IRON ORE PRODUCING COUNTRIES (WITH MORE THAN 2MILLION TONNES PER YEAR)



- China, Brazil and Australia dominate production followed by India
- Production in the former USSR now limited to Russia, Ukraine and Kazakhstan
- Several satellite producing countries started to participate in the seaborne market
- Expected increase in production in Africa did not happen

May join the club of significant producers



Beyond 2018

Mongolia
Vietnam
Sierra Leone
Congo (Federal Republic)
Guinea
Senegal
Uruguay

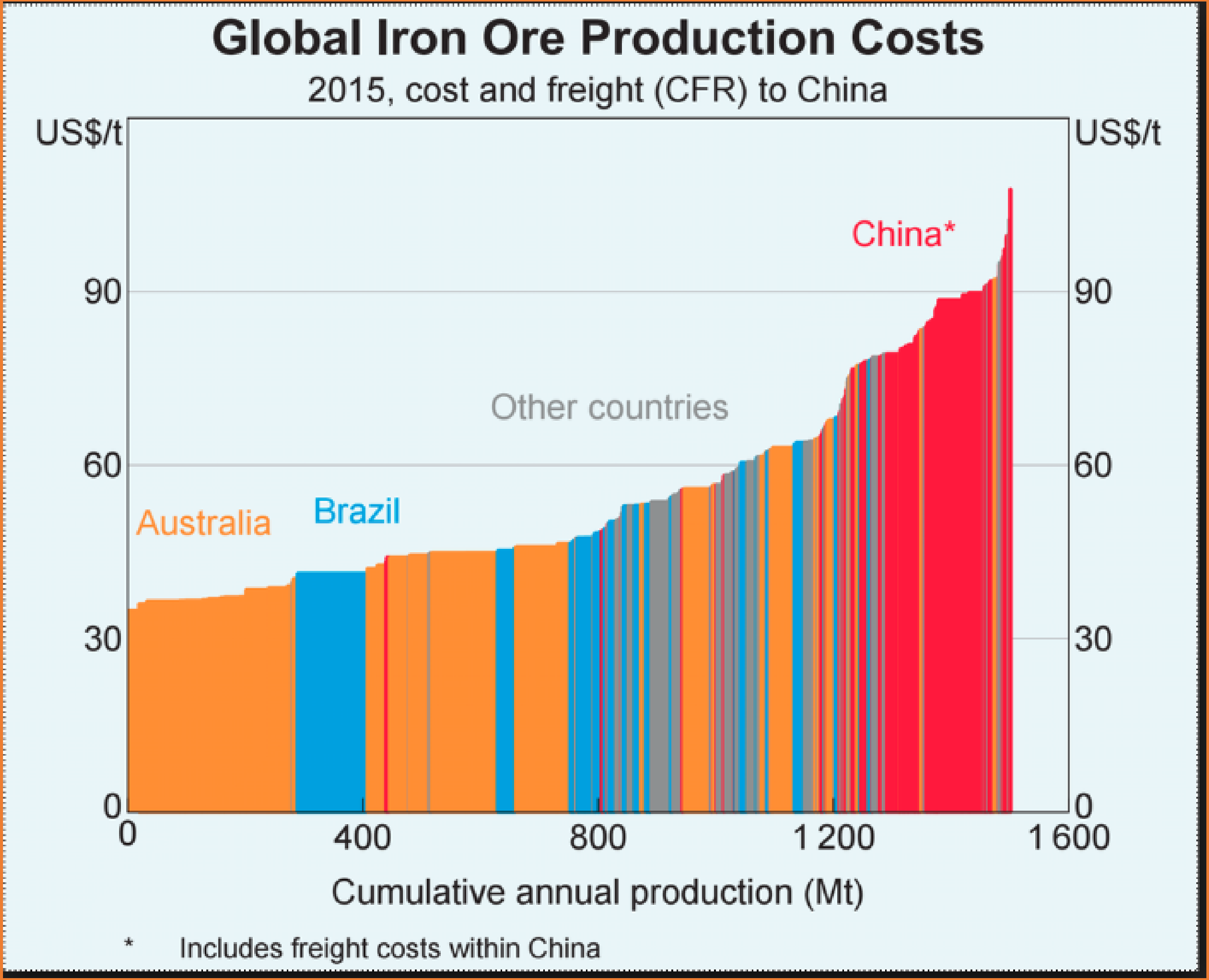
IRON ORE PRODUCTION IN MILLION TONNES PER YEAR (2018)				
Australia	900		Sweden	27
Brazil	490		Mauritania	18
China	340		Mexico	15
India	200		Colombia	8
Russia	95		Liberia	5
South Africa	81		Venezuela	4
Ukraine	60		Peru	4
Canada	49		Chile	3
United States	49		Bosnia and Herzegovina	2
Iran	40		New Zealand	2
Kazakhstan	40		Norway	2

With several main players taking part of the production, like shown in the next slide

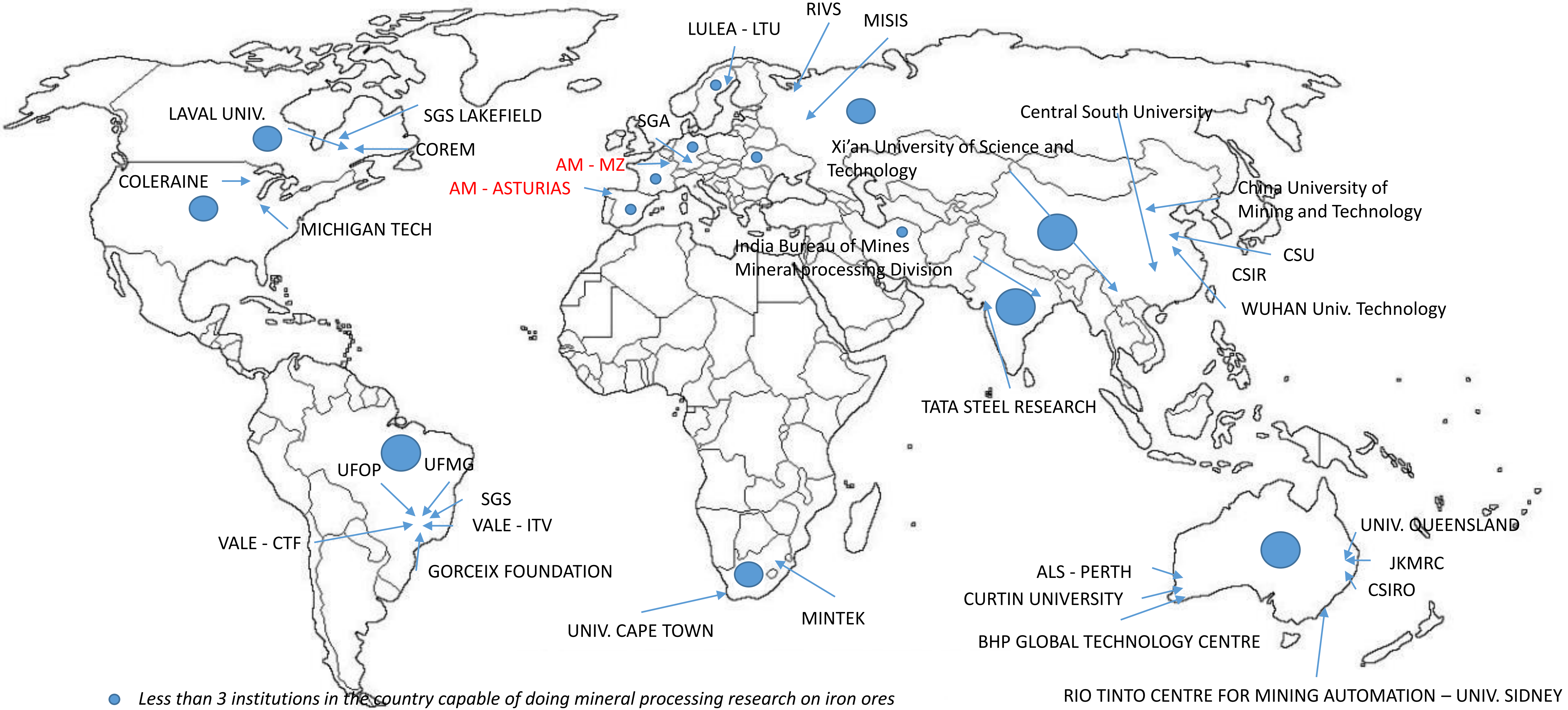
Snim
BAOSTEEL
IRON ORE COMPANY OF CANADA
bhpbilliton
ArcelorMittal
LKAB
FERREXPO
RioTinto
ESSAR
CLIFFS
एन एम डी सी
NMDC
ANSTEEL
鞍钢集团
http://www.ansteel.cn
ANGLO FERROUS BRAZIL
Uma empresa do Grupo Anglo American plc
KUDREMUKH
FERROUS
ANGLO FERROUS BRAZIL
Uma empresa do Grupo Anglo American plc
GERDAU
EVRAZ
arrium
MINING AND MATERIALS
vaerzberg
NAMISA
FMG
vedanta
Mineração
USIMINAS
TATA
TATA STEEL
ALDERON
IRON ORE CORP
sesa goa iron ore
Peña Colorada
CAP
MINERIA
Compañía Minera del Pacífico
VALE
BCI MINERALS LIMITED
CSN
Companhia Siderúrgica Nacional
BAMIN
vallourec
Mount Gibson Iron
Металлоинвест
ATLAS
SIERRA IRON ORE
Baffinland
SHOUGANG HIERRO PERÚ S.A.A.
首钢秘鲁铁矿股份有限公司
KUMBA IRON ORE
حديد البحرين
BAHRAIN STEEL
ENRC
AngloAmerican

Reserves of iron ore [mln tonnes] as of 2015 (Tuck 2016, USGS 2016)

Country	Ore	Iron content
Australia	54,000	24,000
Russia	25,000	14,000
Brazil	23,000	12,000
China	23,000	7,200
USA	11,500	3,500
India	8,100	5,200
Ukraine	6,500	2,300
Canada	6,300	2,300
Sweden	3,500	2,200
Iran	2,700	1,500
Kazakhstan	2,500	900
South Africa	1,000	650
Other countries (about 100)	18,000	9,500
Total world	190,000	85,000


Global Iron Ore Production Costs
2015, cost and freight (CFR) to China
US$/t
US$/t
China*
90
90
Other countries
60
60
Australia
Brazil
30
30
0
0
0
400
800
1 200
1 600
Cumulative annual production (Mt)
* Includes freight costs within China

Examples of Iron Ore Processing research institutions



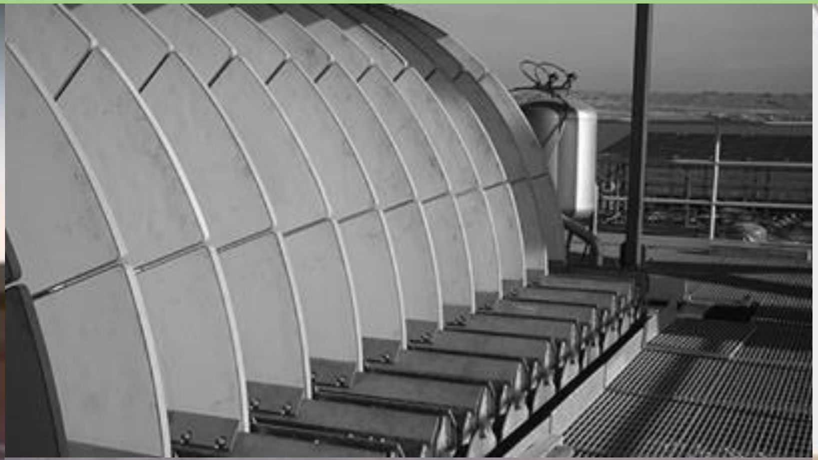
Less than 3 institutions in the country capable of doing mineral processing research on iron ores

More than 3 less than 10

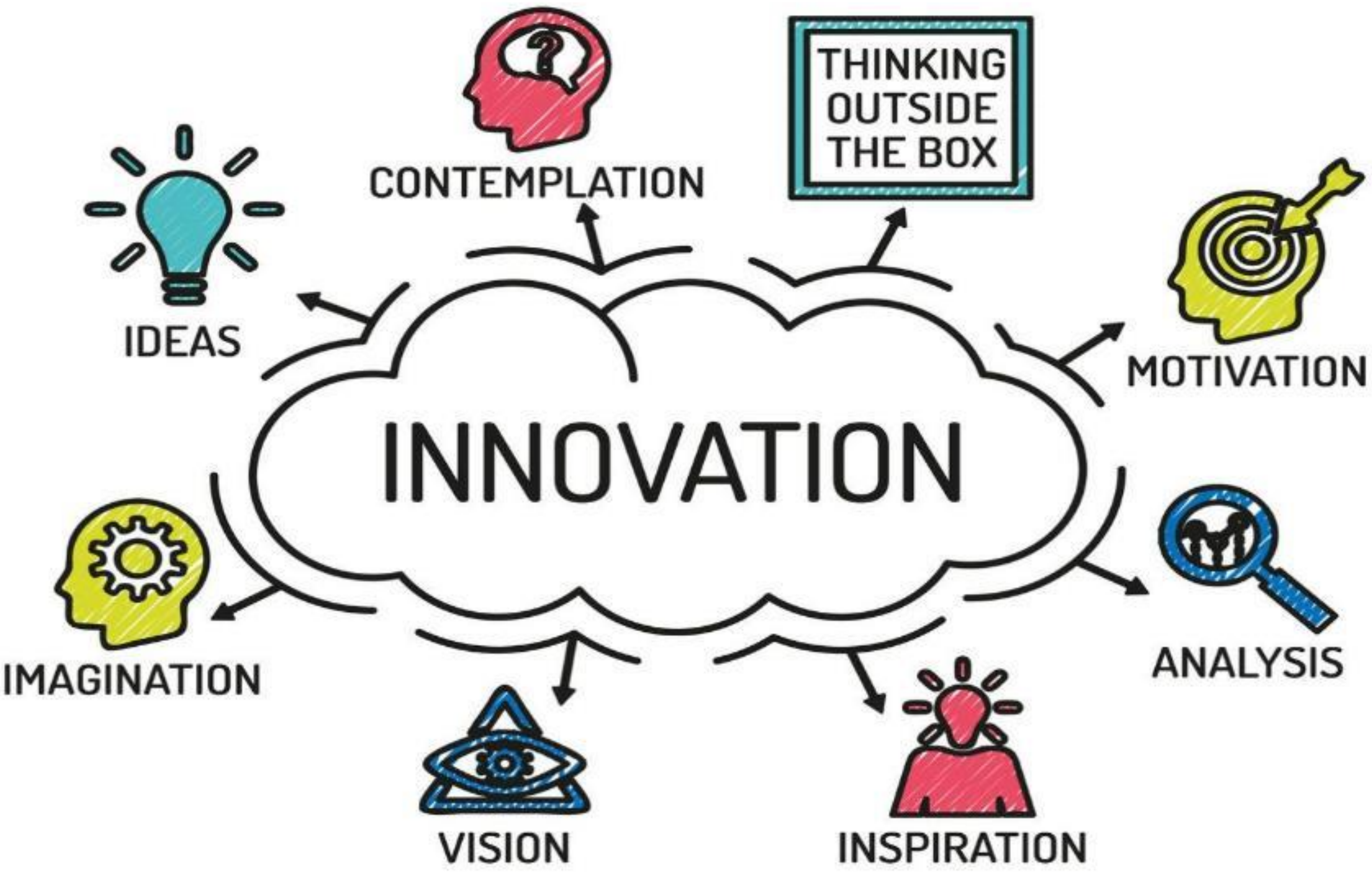
More than 10

Major technological changes in Mineral Processing applied to iron ores

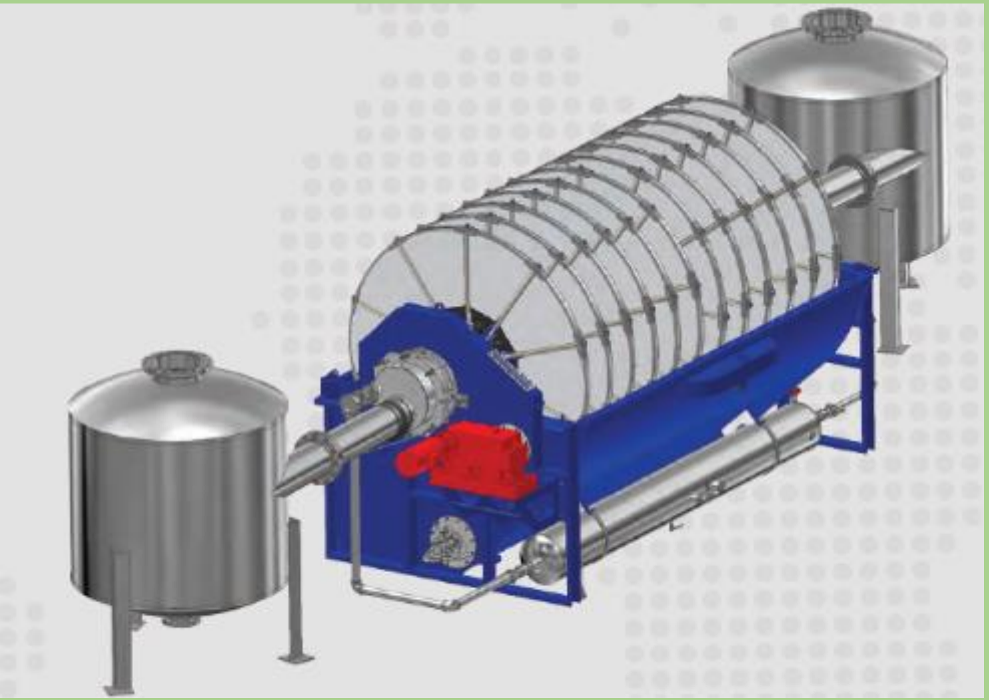
Major technological changes in Mineral Processing applied to iron ores

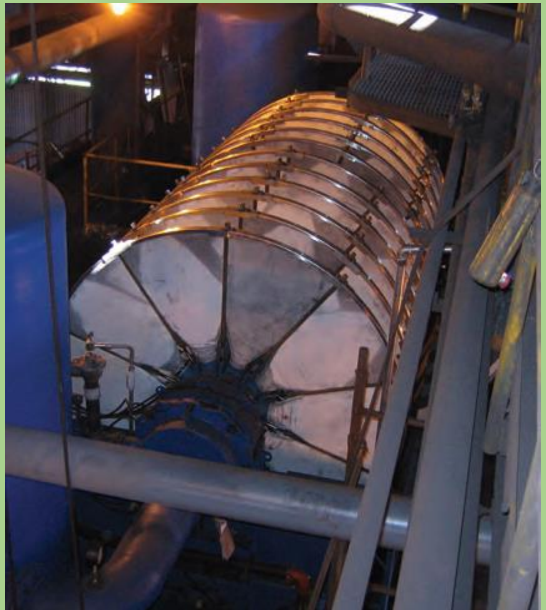



MAIN DRIVERS FOR CHANGE ⟺ IDENTIFYING AND PRIORITISING INDUSTRY NEEDS

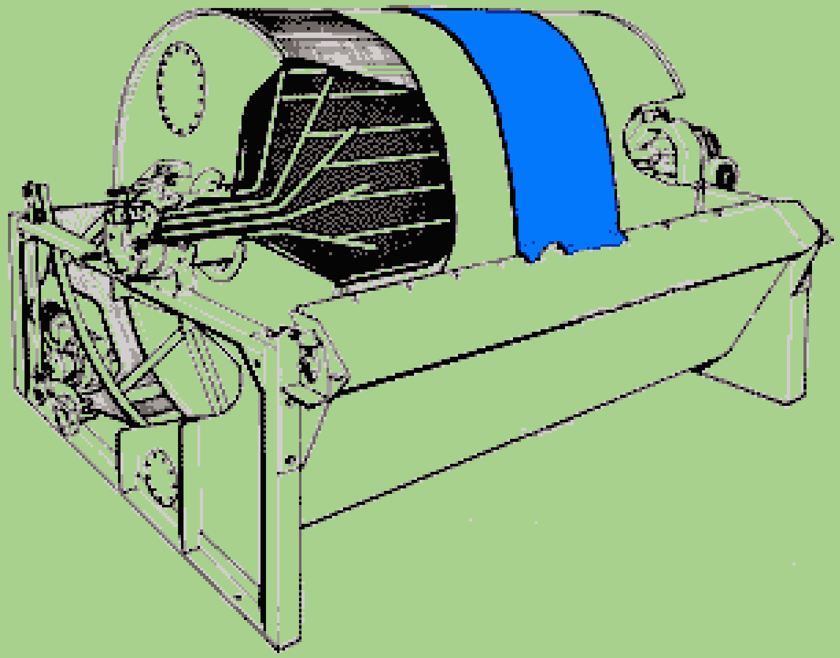


Example of innovation: Vertical Rotary Vacuum DISC Filter versus Rotary Vacuum DRUM Filter





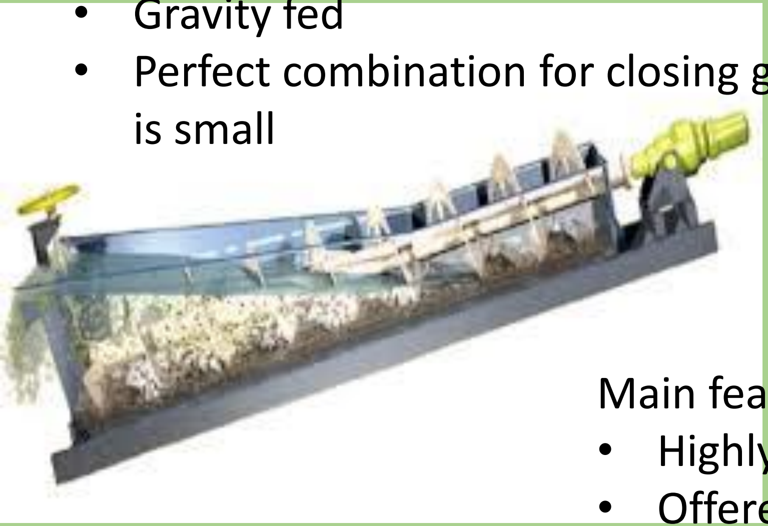
Conceptually the same filtration mechanism applies in both filters but application to an industry that measures its production in million tonnes per year needed innovation. Vertical vacuum disc filters have a lot more capacity per m^2 of footprint than its drum cousin. Typical example of a development to answer a specific need of the iron ore industry.



SCREW CLASSIFIER

Main features:

- Robust
- Large footprint
- Good classification efficiency
- Finest cutting size approximately 75µm
- Gravity fed
- Perfect combination for closing grinding circuits if mill is small



SUCCESS

CAVEX

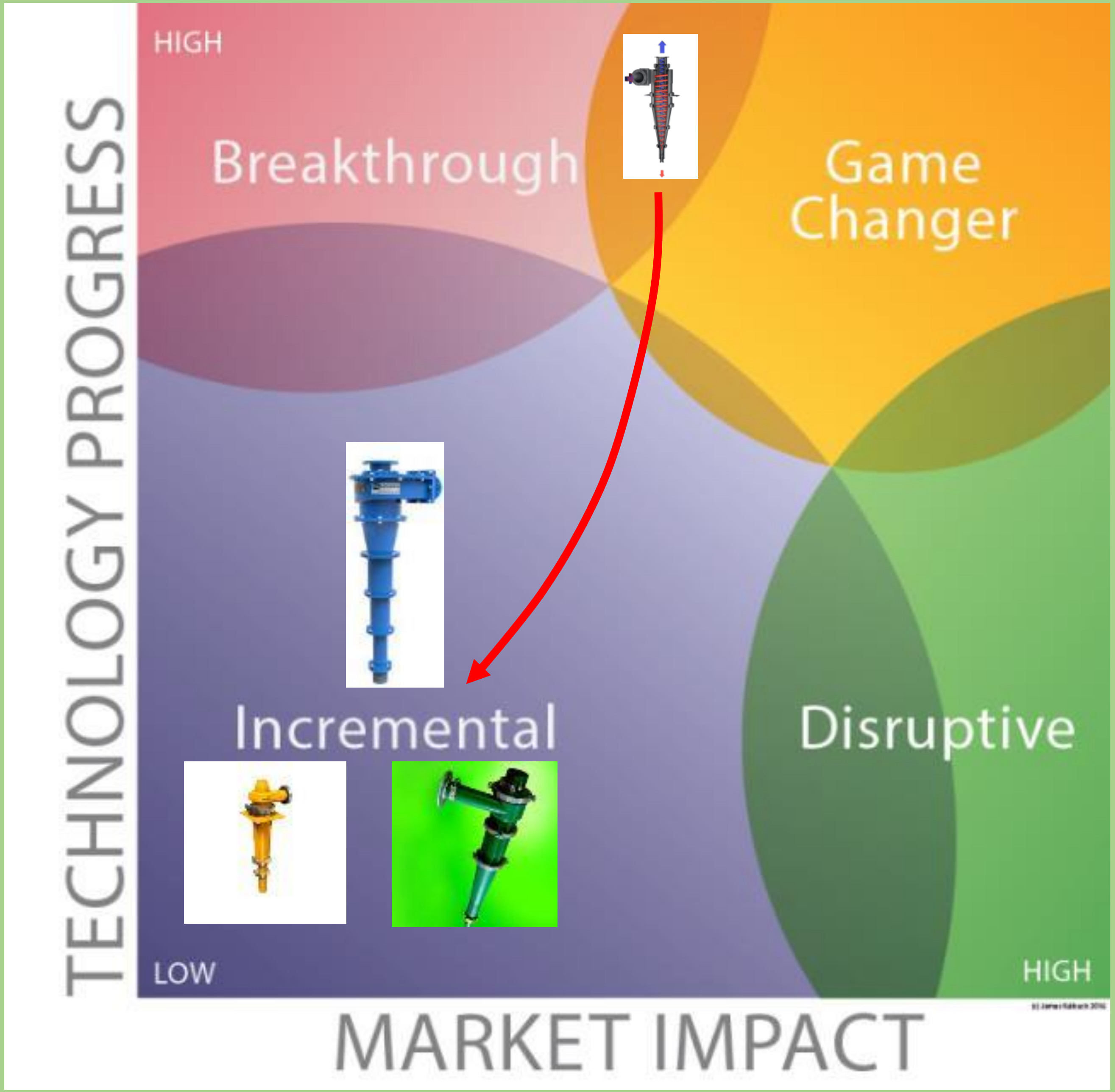
HYDROCYCLONES

Main features:

- Highly flexible, adaptable
- Offered in different sizes for different particle cuts (down to few µm)
- Generally pump fed
- Optimised for higher separation efficiency than conventional hydrocyclones
- Easy maintenance
- Vast choice of construction materials and linings

GMAX

Perhaps the major characteristic leading to the success of hydrocyclones is **ADAPTABILITY**



Innovation Zones - Jim Kalbach, 2012

When firstly introduced to mineral processing , certainly hydrocyclones were extremely important

After that hundreds of improvements took place in the last 60 years. These improvements can be characterised as incremental innovation.

Similar cases are common in the mineral processing field.

Applications then sometimes are shared by other industrial branches.

Air-sparged hydrocyclone (ASH)

- In principle, a very interesting, bold idea
- Combination of hydrocyclone principles with froth flotation
- Promised fast separation and low CAPEX
- In iron ore, too high OPEX due to high collector consumption

FAILURE

Air-sparged hydrocyclone (ASH)

- Only found application outside the mineral industry (waste water treatment, ink recovery, etc.)
- Abrasive conditions of mineral slurries not handled well by ASH

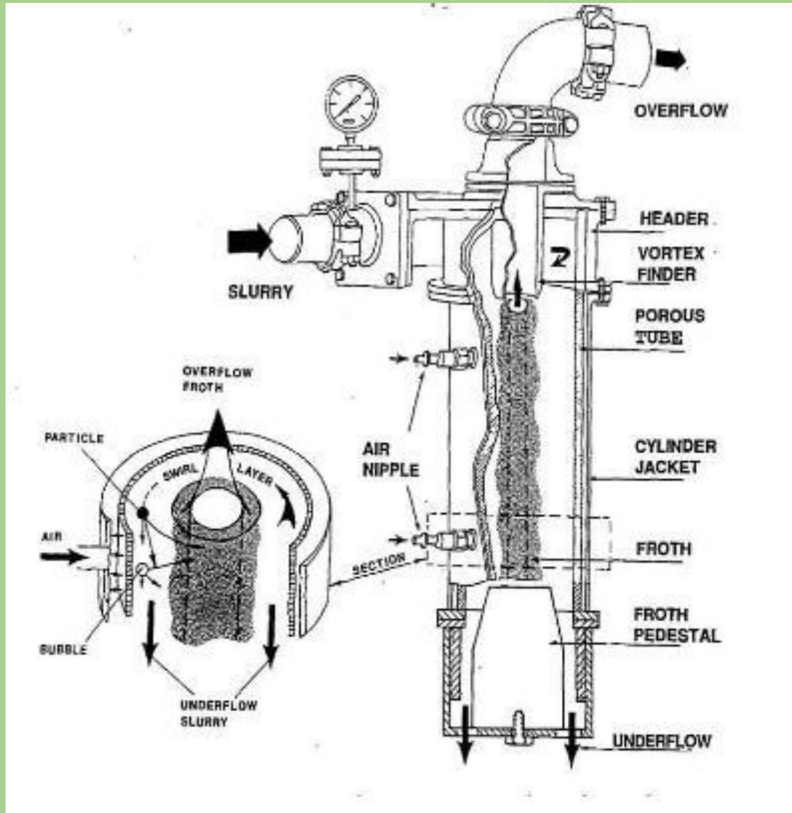
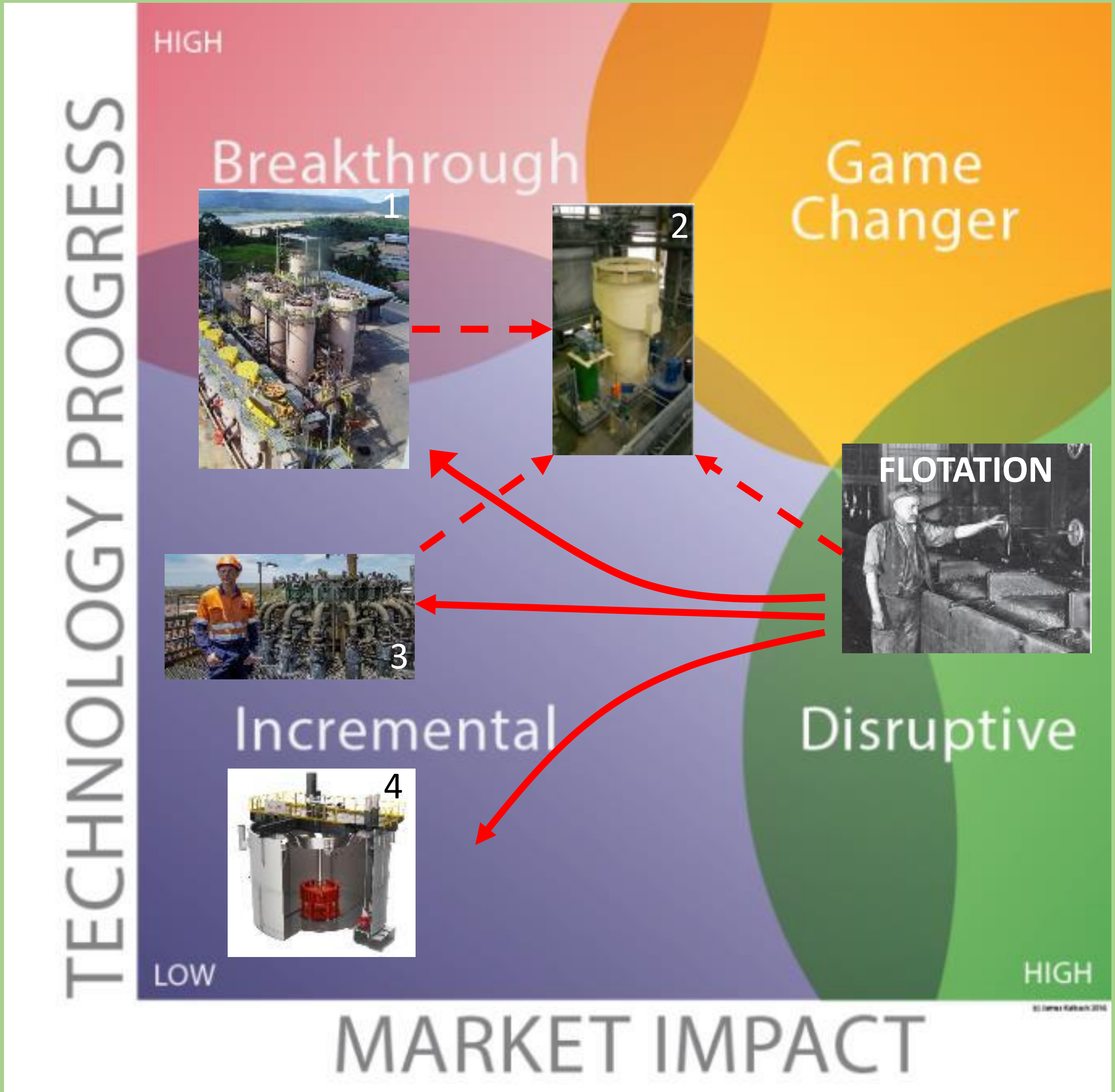


Figure 1. Perspective of the air-sparged hydrocyclone (ASH) (Miller et al., 1988).

1 Column flotation
2 SFR - DFR
3 Pneumatic flotation
4 Mechanical flotation



SOME MILESTONES OF SUCCESSFUL APPLICATION OF NEW PROCESSES AND/OR EQUIPMENT IN THE MINERAL PROCESSING OF IRON ORES

1954 – FIRST INDUSTRIAL APPLICATION OF FLOTATION IN IRON ORES

1950-1960 - FULLY AUTOGENEOUS GRINDING (AG)

1968 – JONES TYPE WET HIGH INTENSITY MAGNETIC SEPARATION (WHIMS - CARROUSEL)

1980's – FIRST APPLICATIONS OF HIGH FREQUENCY SCREENS FOR FINE PARTICLE SIZES

1990's – FIRST INSTALLATION OF HPGRs FOR BLAINE INCREASE AT PELLET PLANTS

1991 – FIRST IMPLEMENTATION OF A COLUMN-ONLY FLOTATION CIRCUIT

1990's – COLUMN FLOTATION BECOMES THE TECHNOLOGY OF CHOICE FOR REACHING HIGH GRADE CONCENTRATES

1990's – INTRODUCTION OF HIGH CAPACITY SPIRALS, ABLE TO TREAT 5TPH PER START

1990's – INTRODUCTION OF HPGR FOR PEBBLE CRUSHING AND FOR COARSE GRINDING

1990's – SLON – VERTICAL PULSATING HIGH INTENSITY MAGNETIC SEPARATORS

SOME MILESTONES OF SUCCESSFUL/POTENTIAL APPLICATION OF NEW PROCESSES AND/OR EQUIPMENT IN THE MINERAL PROCESSING OF IRON ORES

2000's – VERTICAL MILLS FOR FINE GRINDING

2000's – VIBRATING SCREENS BREAK THE BARRIER OF 6X20 ft SIZE

2000's – PRIMARY CRUSHING USING "SIZERS" APPLIED TO IRON ORES

2000's – NEW TECHNOLOGY ON PERMANENT MAGNETS (RARE EARTH) ALLOWS THE INTRODUCTION OF MEDIUM INTENSITY WET DRUM MAGNETIC SEPARATORS WITH VERY LOW OPERATIONAL COST

2000-2010 – RAKE-LESS HIGH CAPACITY THICKENERS (LIKE "ULTRASEP") ARE INTRODUCED

2005 – FIRST APPLICATION OF PNEUMATIC FLOTATION

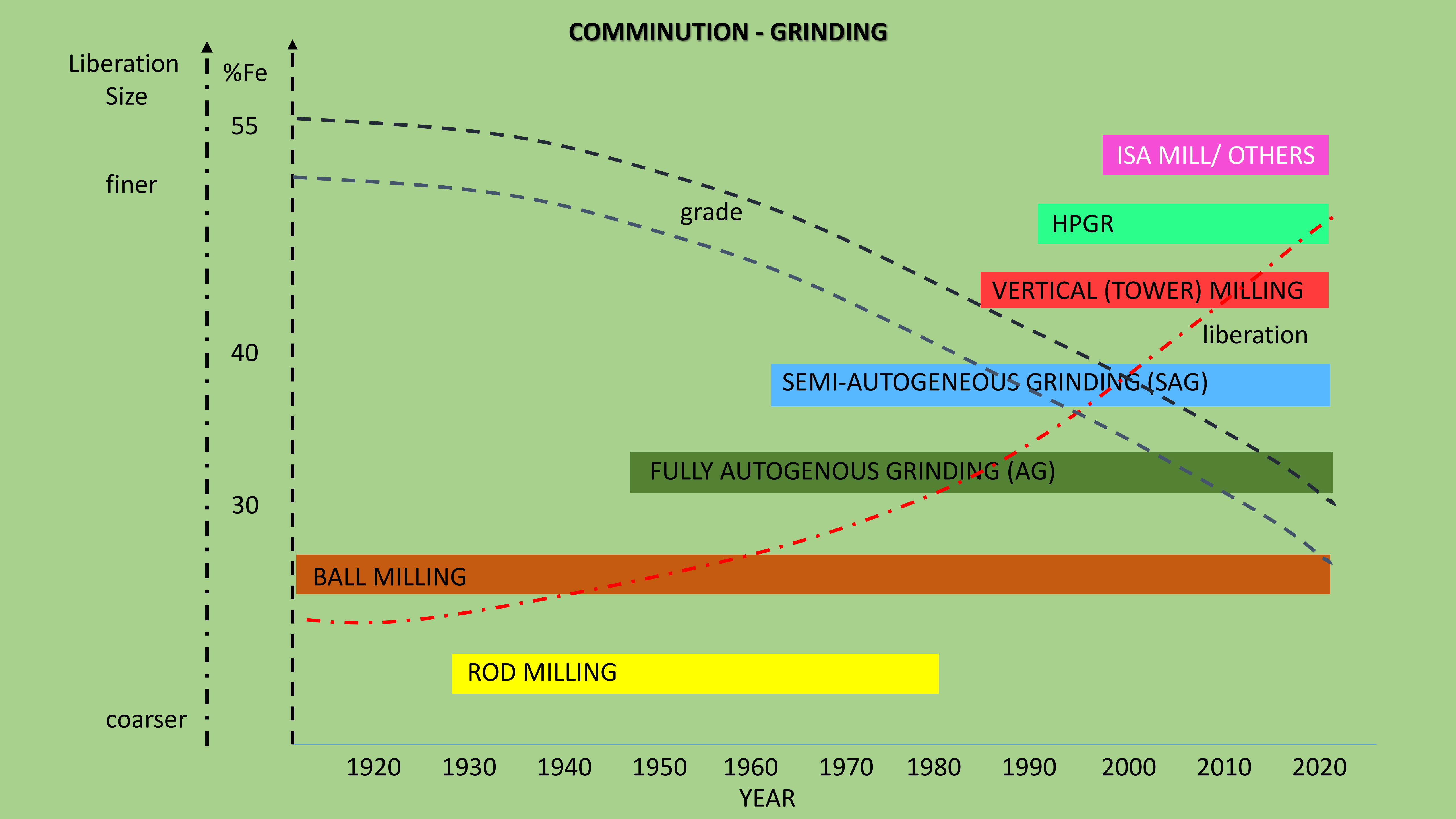
2010 – INTRODUCTION OF CERAMIC FILTERS FOR CONCENTRATE AND TAILINGS DEWATERING

2010 – REV3 CARROUSEL MAGNETIC SEPARATOR (INTERESTING IDEA, HIGH CAPACITY, LOW OPEX BUT TESTED ON THE WRONG TYPE OF ORE AND TIMING)

2010 – HIGH CAPACITY CONCEPT FOR HIGH FREQUENCY SCREENS – STACKSIZER (5, 8, 10 …)

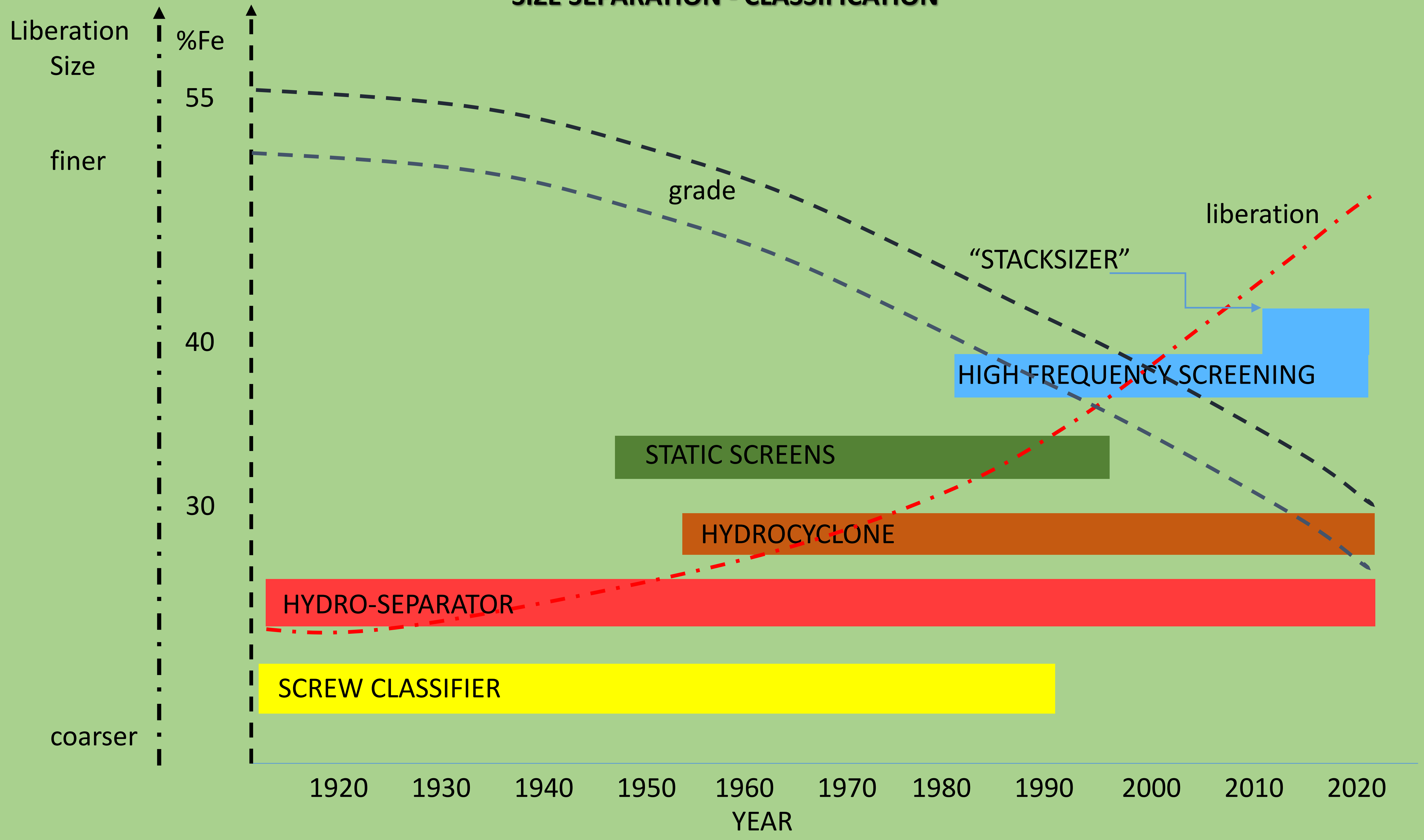
2010's – BELT FILTERS and PRESSURE FILTERS (MAINLY VERTICAL PLATE FILTERS) INTRODUCED FOR TAILINGS DEWATERING

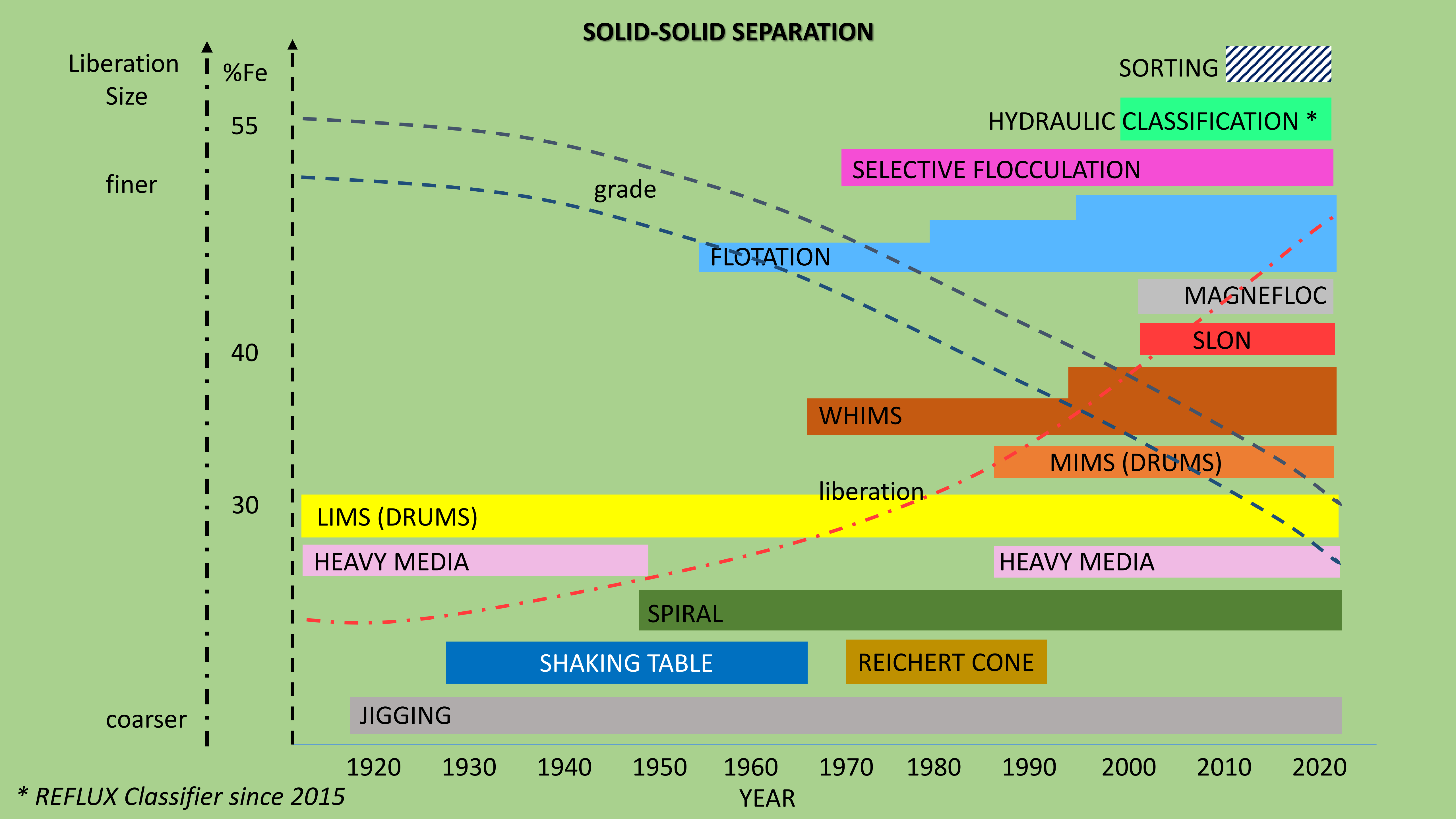
2018 – FIRST PILOT TESTS UTILISING **SFR** AND **DFR** FLOTATION (WOODGROVE) CONCEPTS ARE COMPLETED

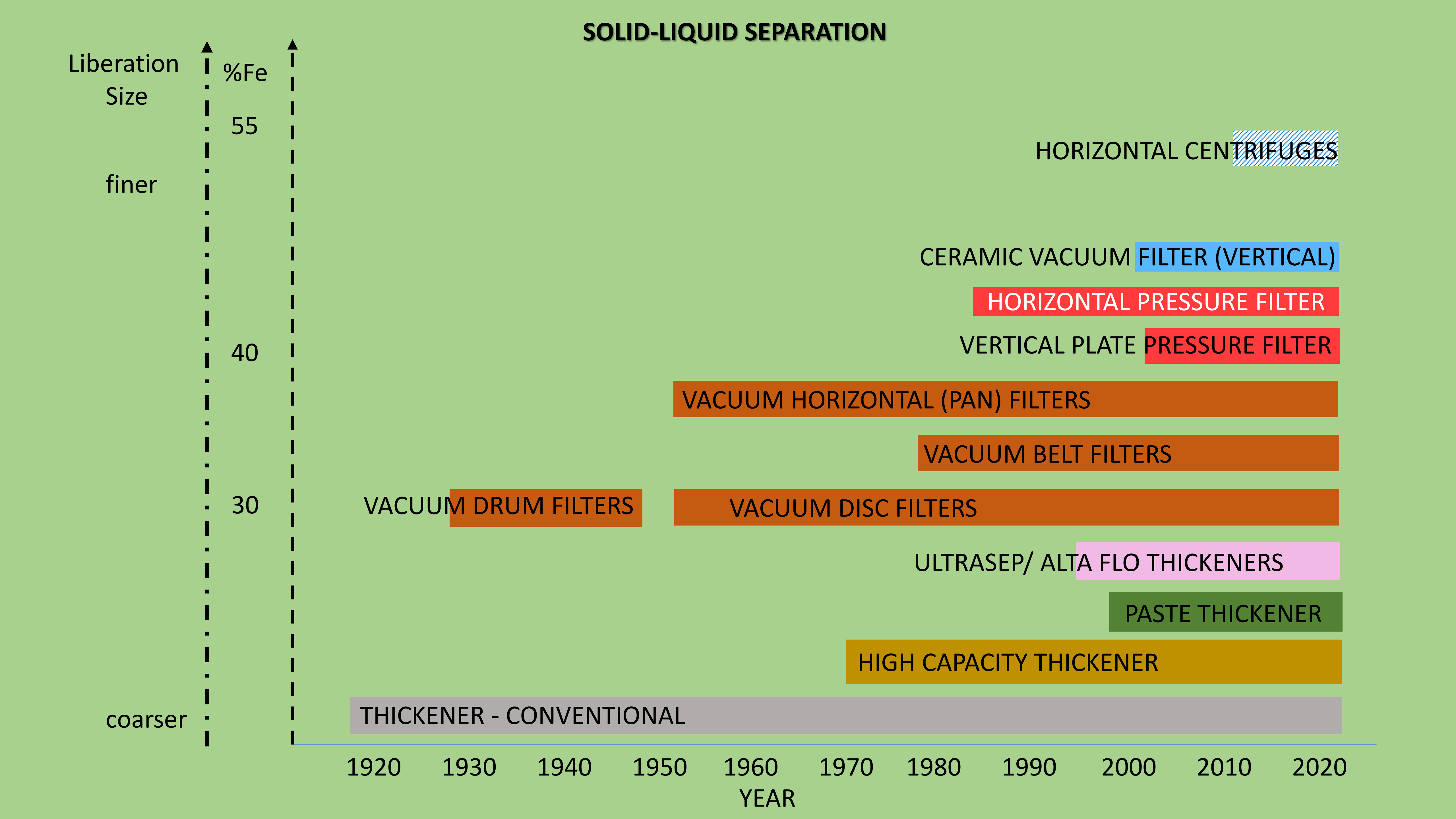


COMMINUTION - GRINDING
Liberation Size
%Fe
55
40
30
finer
coarser
grade
liberation
ISA MILL/ OTHERS
HPGR
VERTICAL (TOWER) MILLING
SEMI-AUTOGENEOUS GRINDING (SAG)
FULLY AUTOGENOUS GRINDING (AG)
BALL MILLING
ROD MILLING
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
YEAR

SIZE SEPARATION - CLASSIFICATION

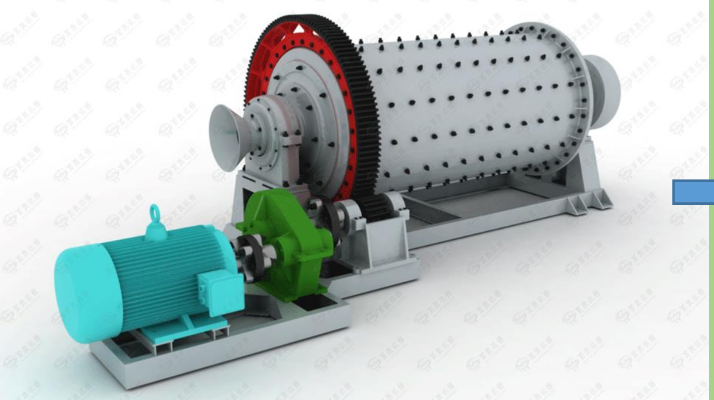


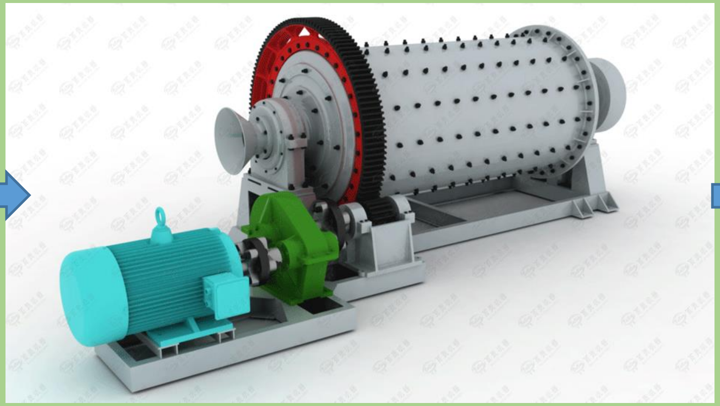

SOLID-SOLID SEPARATION
Liberation Size
finer
coarser
%Fe
55
40
30
grade
liberation
SORTING
HYDRAULIC CLASSIFICATION *
SELECTIVE FLOCCULATION
FLOTATION
MAGNEFLOC
SLON
WHIMS
MIMS (DRUMS)
LIMS (DRUMS)
HEAVY MEDIA
HEAVY MEDIA
SPIRAL
SHAKING TABLE
REICHERT CONE
JIGGING
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
YEAR
* REFLUX Classifier since 2015

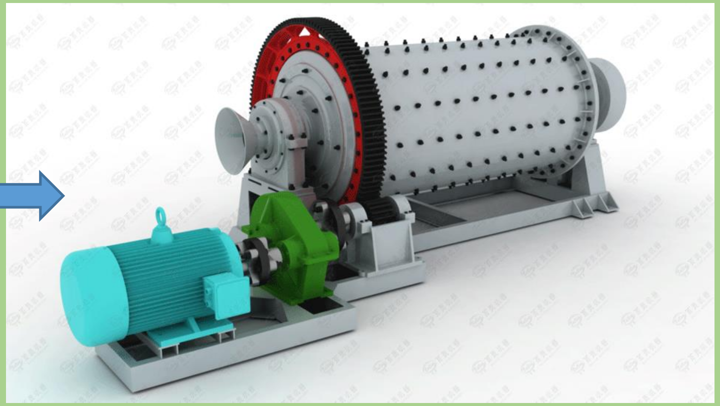

SOLID-LIQUID SEPARATION
Liberation Size
finer
coarser
%Fe
55
40
30
HORIZONTAL CENTRIFUGES
CERAMIC VACUUM FILTER (VERTICAL)
HORIZONTAL PRESSURE FILTER
VERTICAL PLATE PRESSURE FILTER
VACUUM HORIZONTAL (PAN) FILTERS
VACUUM BELT FILTERS
VACUUM DRUM FILTERS
VACUUM DISC FILTERS
ULTRASEP/ ALTA FLO THICKENERS
PASTE THICKENER
HIGH CAPACITY THICKENER
THICKENER - CONVENTIONAL
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
YEAR

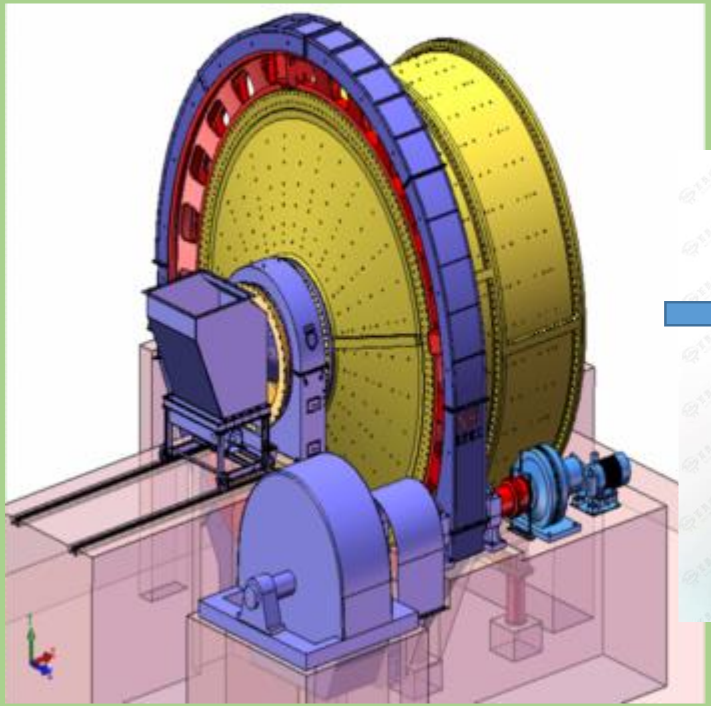
Energy optimisation versus equipment and circuit selection

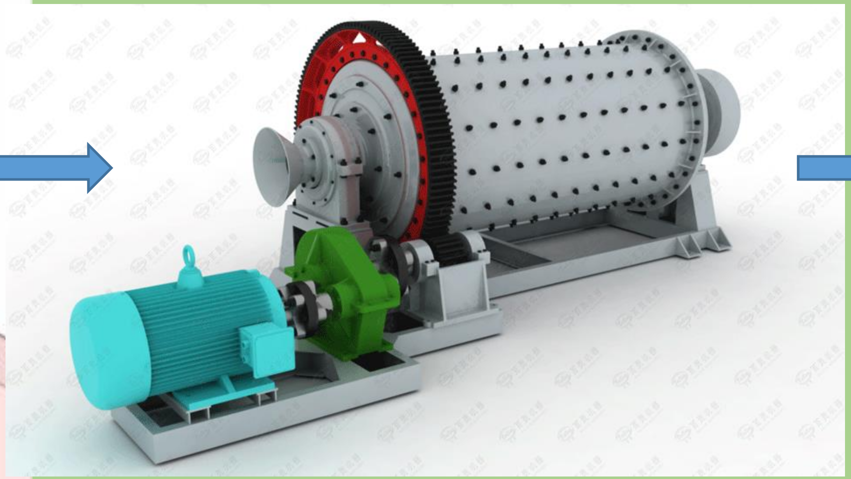
F_{80} =10mm → P_{80} =50µm

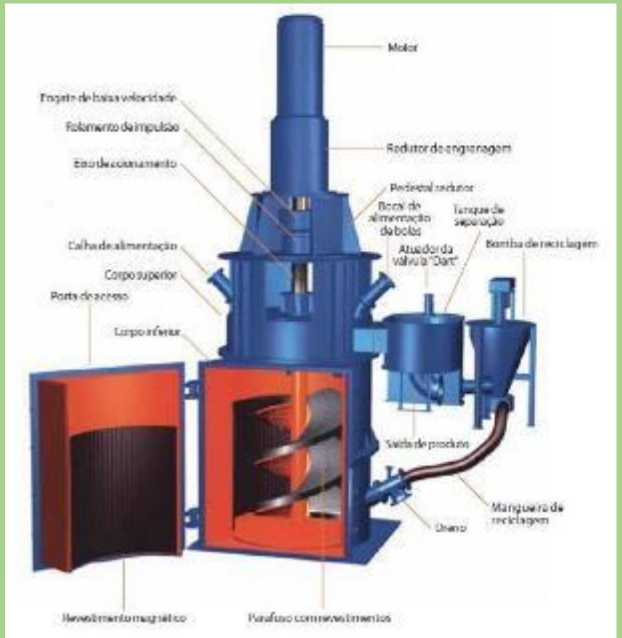






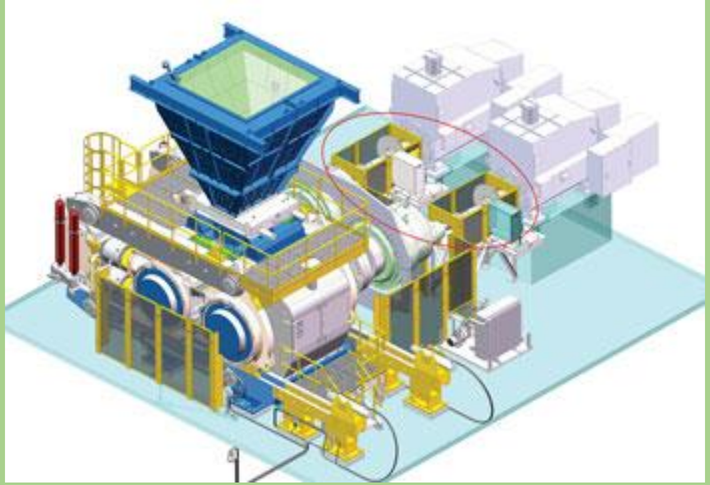


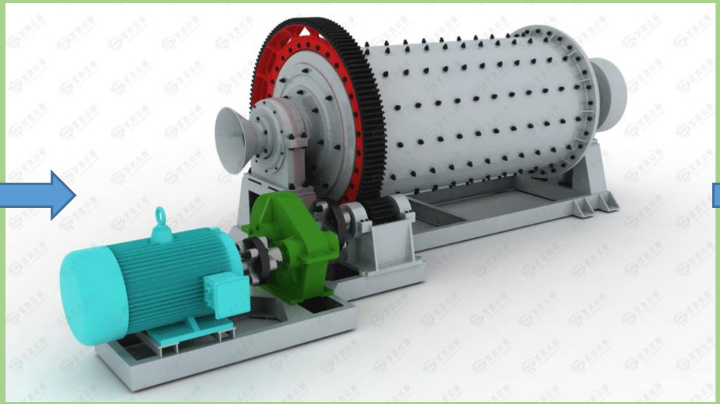


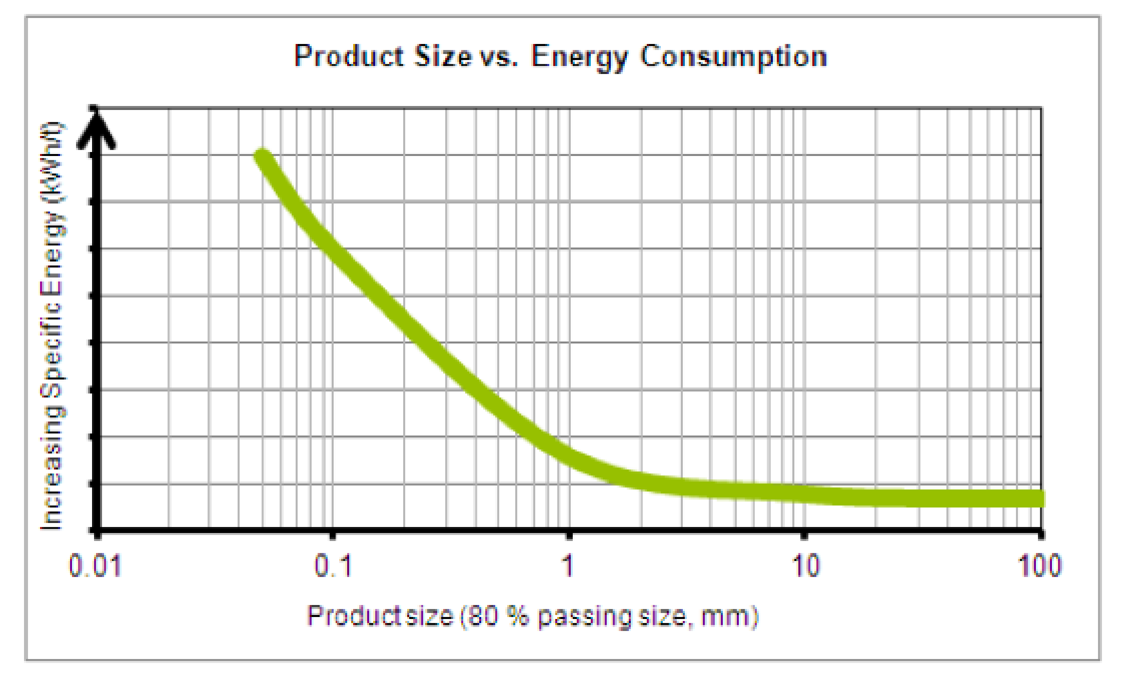


Energy optimisation versus equipment and circuit selection

F_{80} =10mm P_{80} =50µm







We must optimise the selection for each step in order to minimise total energy consumption.

Today the selection of comminution circuit <u>makes or breaks</u> a project in any industry, including the iron ore one!

IF POSSIBLE – PRE-CONCENTRATE!

Drivers for change

Iron Ore Mineral Processing Challenges

Two categories of drivers:

INTRINSIC (related to the mineral resource and ore)

and,

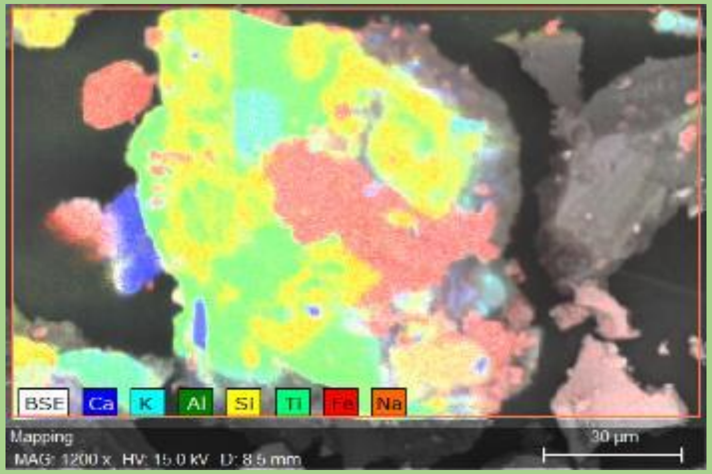
CONTEXTUAL (external factors)

INTRINSIC DRIVERS - examples

W/O ratio increasing (high mining cost)

Fe grade decreasing (low yields = higher OPEX and CAPEX)

Contaminants increasing (more complex beneficiation – several concentration steps needed)



Liberation size decreasing

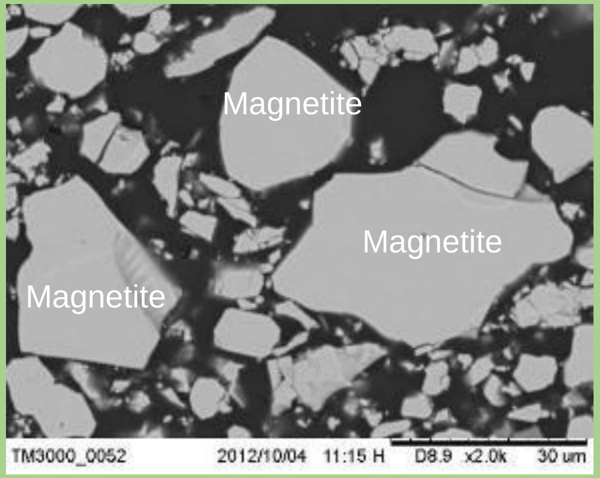
Mineralogical complexity increasing

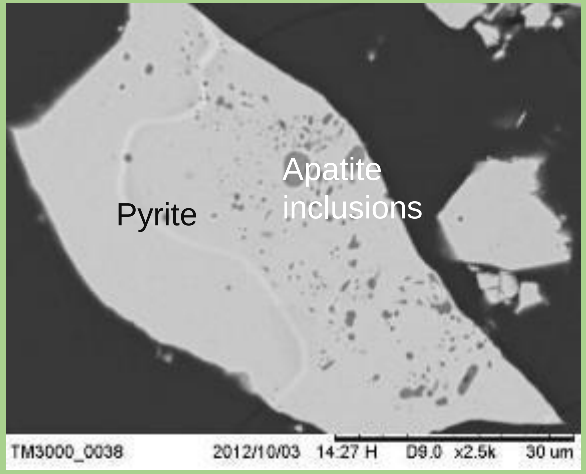
Unusual ore textures becoming more common

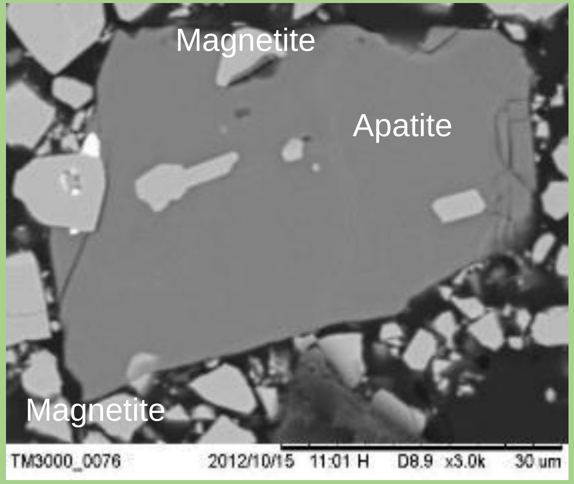
Potential product mix decreasing (consequence of some of the above) – many time only fine concentrate (pellet feed) possible as final product

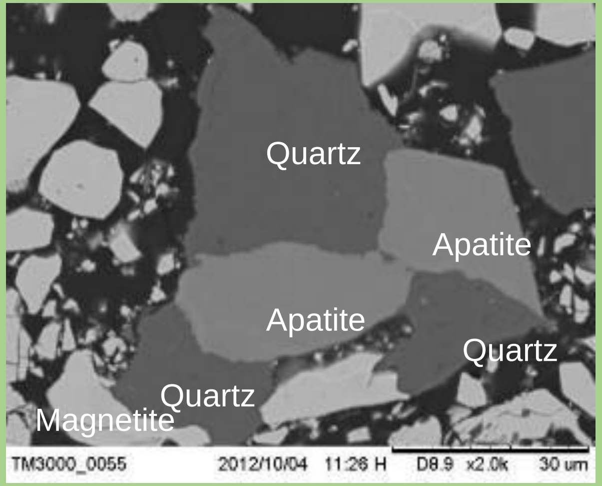
- Complex Mineralogy
- Fine and ultra-fine liberation
- Multi-mineral mixed particles

- All aspects leading to complex flow-sheets composed of several concentration steps
- **Pre-concentration, if possible at all, becomes a MUST!**









CONTEXTUAL DRIVERS – examples Price volatility

Demand/Offer dynamics

- Competitiveness
- Time to develop
- Time to commission
- Time to ramp up
- Time to recover from **catastrophes**

New beneficiation technologies/New iron making routes/High grade deposits development (e.g. SD 11)

Main challenges we are facing now

Summarizing the drivers for change:

- ROM grades going down
- Ores becoming harder
- Liberation becoming finer and finer
- Mineralogy becoming more complex
- Open pits becoming deeper (higher W/O ratios)
- Environmental constraints more and more holistic in nature and tougher in standards
- Social contract more complex and with a multitude of stakeholders
- Increasing of royalties
- Chinese dependency
- Increased lack of skilled working force
- Global economic crisis, repeated times
- Corruption
- Political instability
- Good ore bodies in areas without infrastructure (significant extra CAPEX required)

Addressing the future needs via technological improvements

Finding the right balance between pioneering and being conservative

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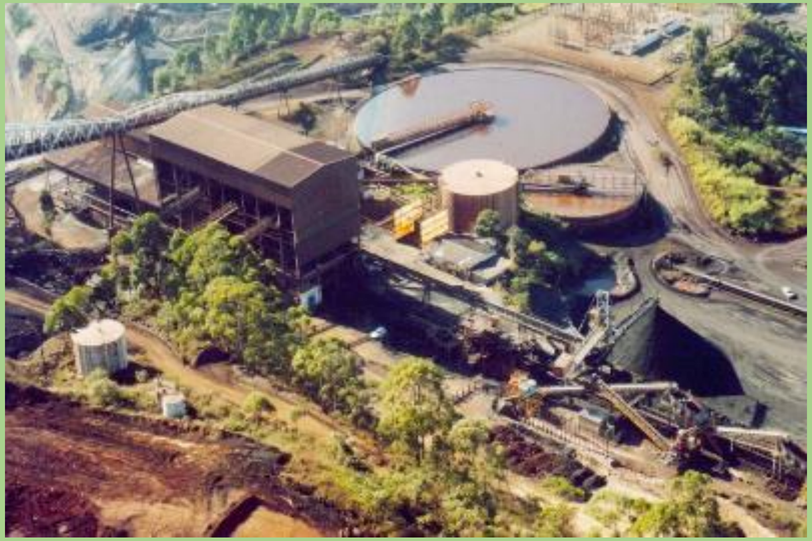

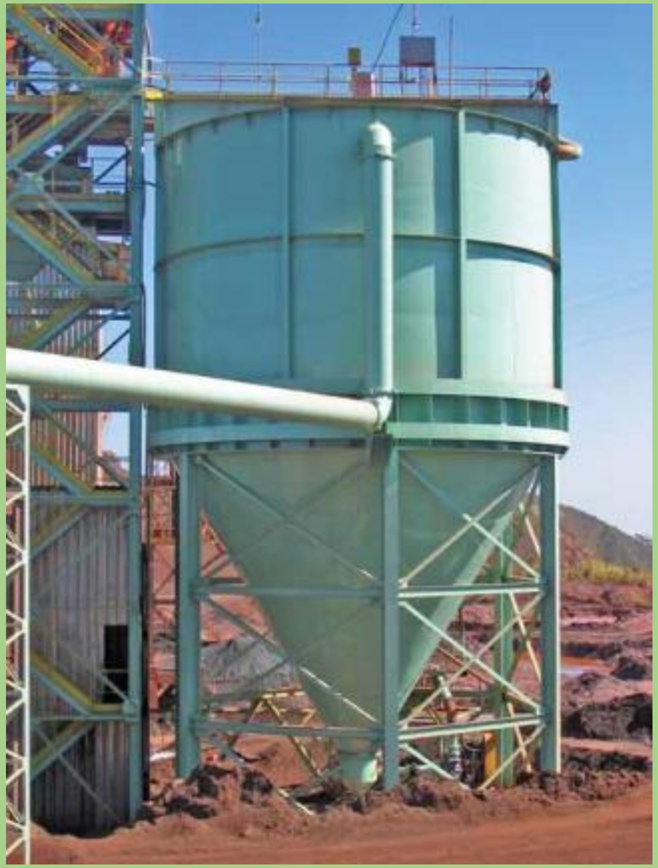

Pioneering: is it worthwhile in processing iron ores?

Examples of successful pioneer applications:

• Autogenous grinding – 1950’s in the USA

• Iron ore processing by flotation – 1950’s in the USA

• Hematitic iron ore reverse cationic flotation – 1950’s in the USA

• Jones type WHIMS large scale application to hematitic ore – 1960’s in Brazil

• Other high intensity magnetic separation methods for goethitic ores – former USSR in the 1970’s and in other countries in East Europe under Soviet sphere of influence

• Very large scale spiral concentration application – 1970’s in Canada

• Steam aided vacuum filtration – 1960’s in the USA and 1970´s in Canada

<u>Examples</u> of successful pioneer applications (<u>continued</u>):

- Selective flocculation for very fine desliming – 1960's in the USA
- Long distance concentrate pipelining – 1970-1980's in Peru and especially in Brazil
- Reverse cationic flotation using column only circuit – 1990's in Brazil
- HPGR grinding – 1990's in Brazil and USA
- High frequency screening for fine separation – 1990's in the USA and elsewhere
- Wet RARE EARTH magnetic separation drums – Brazil in 1990-2000's
- Magnetic Flocculation for desliming of finely ground magnetite concentrates – Mexico in 1990's
- SLON magnetic separation – China in the 1990's

Common to all pioneering actions – **all plants that firstly applied these innovations are still operating today, in a profitable way!!!**

<u>**Examples**</u> of other pioneer applications (including some that are still to be proven)

- Ceramic filtration of concentrates
- Flotation tank cells (large to very large volume)
- High rate thickening
- Pneumatic flotation
- Tailings filtration using conventional horizontal filters
- Tailings filtration using ceramic filter
- Tailings paste thickening
- "Vertmills"
- On-line, real time chemical analyses
- Mine face mineralogy using infrared spectroscopy
- On-line particle size distribution by image analysis
- Mine-to-mill integration

Conventional tailings dams
FAILURES

Common to all pioneering actions – **iron ore plants applying innovations should be considered as <u>"followers"</u>, i.e., these innovations were, <u>in most cases</u>, firstly applied in other fields of the mineral industry before being used in iron ores**

Concluding remarks

- Iron is abundant in our universe
- The properties of iron and its alloys (steel) make the whole difference, allowing a very wide range of applications
- After a period of high gains, iron ore miners are now facing more and more challenges in all fronts, especially in the beneficiation of lower grade, more contaminated iron ores with complex mineralogy

Concluding remarks (continued)

- Pioneering could be part of the answer to the challenges we are now facing, as history show us that when we decided to utilize pioneering technologies we eventually succeeded.

- We should learn from other areas of the mineral industry, in which continuously decreasing ROM head grades were counteracted by applying some (daring) innovative solutions (moving from “followers” to “developers”)

Concluding remarks (continued)

- TRENDS:
  - More efficient comminution (maximizing size reduction at the lowest energy consumption possible by selecting the most adapted comminution circuit for each ore).
  - More efficient solid-liquid separation (maximizing water recirculation and tailings solids content and, at the same time, minimizing product moisture).

Concluding remarks (continued)

- TRENDS:
  - Speedy commissioning and fast ramp-up, all dependent on very well conceived plant design (should we start to incorporate clauses in the contracts with engineering companies that would allow bonus for truly outstanding design jobs?).
  - Bring equipment manufacturers up to speed with our needs. Work directly with them for tailor-made solutions to iron ore processing needs (being more open minded regarding future challenges in difficult to treat iron ores).

Concluding remarks (continued)

- TRENDS:
  - Find the right combination of concentration techniques for treating each ore, bearing in mind that simplicity and flexibility are key factors for a smooth running beneficiation plant.
  - Finding the right combination of concentration techniques for a given ore is FULLY dependent on a very well done mineralogical characterization (we should never forget we are always dealing with minerals not with chemical compounds).
  - WE ARE AFTER EFFICIENCY IN ALL AREAS, ESPECIALLY IN ENERGY AND WATER UTILISATION.
  - Utilisation of AVAILABLE TECHNOLOGIES will become inevitable to decrease overall environmental footprint and impact.
  - NEW PLANTS NECESSARILY HAVE TO ADDRESS THE NEEDS OF LOW OPEX AND CAPEX ASSOCIATED WITH RESPONSIBLE AND ZERO RISK TAILINGS MANAGEMENT.

Some questions we should start trying to answer:

1. How much innovation do we need in iron ore processing today?

2. How do we address the challenges of lowering grade and yield by innovation? In other words, is innovation a solution (or a part of the solution) to our current challenges? If so, how should we act?

3. Should we dare to be “developers” instead of “followers”?

4. Should we approach our customers in a different way? How to develop win-win partnerships? In other words, how should we proceed to understanding our customers real needs?

XXVIII ENTMME
ENCONTRO NACIONAL DE TRATAMENTO DE MINÉRIOS E METALURGIA EXTRATIVA

THANK YOU VERY MUCH

ArcelorMittal