Abstract. The article is focused on the study of the mineralogical resources and particularities of the iron ore from Kirunavaara, Sweden, in connection with pellets making and steel making technologies. Having in view the actual trend for the use and the management of the non-renewable resources it is proposed a study about the impact of the iron ore exploitation and manufacturing on the sustainable development in the field of the metallurgical industry. The objectives of the paper include the following activities: analyse of the situation on the field in Malmberget and Kirunavaara, a study of the mineral resources including the basic and auxiliary composition of the ore, a study about the properties and geo-economical particularities in Malmberget and Kirunavaara in the conditions of sustainable development and the impact on the steel quality. An important aspect will refer to the history and the general characterisation of deposits from Malmberget and Kirunavaara having in view the final goal of the researches about the mineralogical particle, ore pellets making, and agglomerating methods.

Key Words: metallurgical resources, sustainable development, properties.

Introduction. Sweden is the most important producer of iron ore in Europe, having a mining area with several economic deposits. This are epigenetic Cu-Au ores (location: Pahtohavare, Aitik), stratiform Cu deposit (Viscaria); skarn iron ore (Stora Sahavaara) and apatite iron ores of the Kiruna type (Kiirunavaara, Malmberget) (Figure 2). The apatite iron ores have been in focus for genetic discussions over 100 years. Mainly there are magmatic model and a hydrothermal model. Because not all the particularities of the apatite iron ores are easily explained with a single genetic model, a combination of these two models, a magmatic–hydrothermal process is suggested to have formed the Kiruna and Malmberget deposit.

Major companies, which have a long tradition of mining, coexist with minor companies, in order to extract metals and minerals, with iron ore, as one of the most important commodity for demanding global market. The crude steel production has increased in the last few years, so the market is tough. This is the main reason for what the iron ore producers offer products of good quality and knowledge about the included relevant elements of the product.

Today, the mining industry works in different ways to solve the problems of a process mineralogical character and the producers having control over the refinement process; they are trying to do this in a profitability way, in times of increasing competition and when the steel market is turning downward (Lund 2009).

The main plan for the activities in Kirunavaara, in order to study the impact of the mining effects on the environment, is presented in Figure 1.
Figure 1. The main plan of the work and of the activity in Kirunavaara.
History and actuality. The deposit from Malmberget is known since 1735; there are many pioneers in the history that have tried to make deposit profitable. But an eternal problem has been the transportation of ore across the Norrbotten wilderness. The discover of a new method of steel elaboration by blasting air, in 1878, made the giant ore reserves in Kiruna and Malmberget very attractive and LKAB (Luossavaara – Kiirunavaara Aktiebolag) was established in 1890 to exploit these deposits. To increase the profitability, a railway was built up in 1892, between Malmberget and Luleå. At the beginning, the Malmberget ore was pit–mined, but since 1925, all production has been underground (LKAB 2006). Nowadays, LKAB is contributing to 90% in the production of the iron ore in Europe, from two large underground mines, at Malmberget and Kiruna.

The first pelletizing plant began to operate in Malmberget in 1955 (LKAB 2006). Today, the company is an important supplier of iron ore pellets and provides the global market by 2–3%.

Geological description. The studies on the host rocks, in the Kiirunavaara Group, to the ores, have indicated a volcanic origin. The ore body is large and extends approximately 4 km along strike (Figure 3). It is at least 1.7 km deep and varies in thickness between 50 and 200m, contains more than 60% iron and dips 60-70° towards east. It is crosscut by several dikes of diabase rock along with at least one dike of granophyre, which is older than de diabase (Cliff et al 1990).

The most common gangue minerals are: apatite, actinolite mineral and calcite. In addition micas, chlorite, pyrite, chalcopyrite, talc, anhydrite, gypsum, titanite and allanite are also present within the ore body in minor amounts.

The content of impurities in the ore body differs in between different parts, where the areas richest in phosphorus are located at the upper levels as well as in the northern end.

There are five categories to express the quality of the ore: B1, B2, D1, D3 and D5. The ore B is poor in phosphorus, whereas the D ores is rich in P. B1 is the purest ore type and has an iron concentration of more than 65% Fe. The B2 has iron content lower than 65% and is characterized by its elevated content of silicates (Nordstrand 2012).

Apatite iron ore, known as Kiruna type ore (Geijer 1931) is a category of iron deposits associated with volcanic rocks or high-level intrusions, which have variable concentrations of magnetite-fluorapatite-actinolite and range in age between Proterozoic and Cenozoic. In Norrbotten are around 40 deposits of this type and they are concentrated in the Kiruna-Gallivare area (Villegas & Nordlund 2008). This region holds one of the largest concentrations of magnetite-apatite ores in the world. They usually
occur as tabular bodies that are interposed in the middle-upper part with rocks of the Kiirunavaara Group.

Figure 3. Model of the Kirunavaara ore body (source: LKAB).

**Manufacturing process and transportation.** The mining method used is sublevel caving. In the mines, the ore is blasted and then crushed into lumps of less than 100 mm before it is hoisted to the processing plants at the surface level. The upgrading of the crude ore into pellets and fines continues at the processing plants. First, the ore is milled to a fine powder and the minerals are separated from the gangue by magnetic separators. Further separation is made by flotation. The concentrate is mixed with water and additives to form slurry. In the pelletising plant the slurry is dewatered, filtered and binders are added. The mixture is then fed into drums or on discs and rolled into 7-16 mm balls (green pellets). The green pellet is then dried before it is sintered. The sintering is either taking place in a rotary kiln at 1250°C or on a belt conveyor. In the sintering process the grains are bonded together into pellets with considerable higher strength. During this process, magnetite $\text{Fe}_3\text{O}_4$ is converted to hematite $\text{Fe}_2\text{O}_3$ and heat is generated. After sintering, the pellets are cooled to a temperature less than 50°C. The strength of the iron ore pellets should withstand the long transports by rail, ship and storage in e.g. silos. They should also withstand the beginning of the reduction process in the blast furnace without fragmentizing in order to ensure a good gas flow (Gustafsson et al 2009).

**Transportation and handling systems.** The finished products from the processing plants in Kiruna and Malmberget are transported to the customers by rail and by ship via the ports at Narvik and Luleå (Figure 4). The railway connects Narvik in Norway, via Kiruna and Malmberget, with Luleå at the Swedish coast in the Baltic Sea. Iron ore products from Kiruna are transported to Narvik for customers in the European market and the rest of the world. From Malmberget the products are transported to Luleå for customers in the nearby and countries around the Baltic Sea. Twenty-six (26) million tonnes per year (2011) are transported on the railways to the shipping ports. To increase the capacity of the railway system to 40 million tonnes per year 2015, new investments have been decided. The cars that are currently in operation on the ore railway carry a payload of 100 tonnes and each train set consists of 68 cars. In the port in Luleå, ore
products are mainly stockpiled in three silos, with a total capacity of 135,000 tonnes. The annual iron ore passing is 10 million tonnes (2011) for this port (Gustafsson 2012).

Figure 4. Actual railway from Kiruna to Narvik (photo: Dan Constantinescu, July 2009).

Local consequences of mining exploitation in the context of sustainable development. A major effect of mining exploitation in Kiirunavaara zone is the subsidence of the hangingwall. It is characterised by two deformation zones - discontinuous deformation zone and continuous deformation zone (Figure 5).

Figure 5. Surface subsidence zones of the hanging wall at Kiirunavaara mine (after Villegas Barba 2008).

Discontinuous deformation zone. This zone is characterized by large surface disturbances affecting limited regions. Features such as tension cracks, steps and chimney caves normally appear in this zone. Tension cracks are formed by extension strain with a tendency to develop along sub-vertical discontinuities striking parallel to the ore body (which is the most predominant joint set). Steps, which started as tension cracks, define the extension of failed wedges or blocks. Chimneys form in the failed rock mass under stress relaxation where individual rock blocks move vertically through flow channels after ore draw.

Continuous deformation zone. In this area, there is a smooth lowering of the ground surface detected only by periodic surveying. This zone, which extends to around 150–200 m beyond the limit of the discontinuous deformation zone, shows only elastic deformation or continuous non-elastic strain (Villegas Barba 2008).
The images of the failure cracks were realised in mine, with different occurrences and in distinct sections of mine levels. The interpretation of geophysical measurements (Magnor & Mattsson 1999) has conducted on features localisation (Figure 6).

![Figure 6. Lineaments and geotechnical domains (after Magnor & Mattsson 1999).](image)

The rocks quality was determined by empirical analyses of mine sections, to evaluate the hanging wall subsidence, for each domain (Bieniawski 1976).

**Domain I** - it has the following characteristics (Figure 7):
- heavily jointed rock mass with small-size caved rock;
- there is no clear limit between different quartz porphyritic rocks;
- the crater of the sinkholes keeps stable for a few days or months;
- rock type: quartz porphyry A and B;
- stress condition: expected uniform state of stresses.

![Figure 7. Domain I (Vilegas & Nortlung 2008).](image)
Domain II - it has the following characteristics (Figure 8):
- this area shows less weathering than Domain I;
- low fracture density;
- visible step failure on ground surface;
- the crater of sinkholes keeps stable for long periods;
- rock type: light color quartz porphyry;
- stress condition: probably stress concentration (pillar effect); expected large variation by influence of geological structures.

![Figure 8. Domain II (Vilegas & Nortlung 2008).](image)

Domain III - it has the following characteristics (Figure 9):
- this zone is characterized by brown color porphyry rock (zone B), which shows smooth step-type failures at surface;
- slope shows a well-defined high scarp face and the crest cover by a waste dump;
- water level is higher than Domain II and lower than Domain IV;
- rock type: quartz porphyry B;
- stress condition: higher ground level than Domain II which could create higher vertical stresses than Domain I and II.

![Figure 9. Domain III (Vilegas & Nortlung 2008).](image)

Domain IV - it has the following characteristics (Figure 10):
- many lineaments cross this area;
- low fracture density;
- crater of sinkholes keeps stable for long periods;
- rock type: red to pink quartz porphyry;
- stress condition: medium stress; high water pressure.
Conclusions. Investigating the mining area, a major local consequence is the subsidence of the hanging wall. It has a negative impact on the environment, because the surfaces and the basement are extending to the Kiruna city and to the railway. Continuous or discontinuous subsidences are describing the mine walls deformation. They are monitored periodically, using different techniques of control and fissured surfaces topographies. Therefore, simultaneous with mining techniques accession, there is a downfall reflected by the caving of the mine walls and its expansion to the town. It represents an important local consequence and has a negative impact on the environment. Studying the mineralogical resources and their properties, as non renewable resource, it is possible to understand the complex connections between the properties of the iron ore, steel production, sustainable development of the metallurgical industry and the environment protection in the Northern Scandinavia.

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