

Geological and Rock Mechanics Perspectives for Underground Coal Gasification in India

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Abstract. The geological resources of coal in India are more than 308 billion tonnes upto a depth of 1200 m, out of which proved reserve has been reported at around 130 billion tonnes. There is an increasing requirement to increase the energy extraction efficiency from coal as the developmental prospects of India increase. Underground coal gasification (UCG) is a potential mechanism which may be utilized for extraction of deep-seated coal reserves. Some previous studies suggest that lignites from Gujarat and Rajasthan, along with tertiary coals from northeastern India can be useful from the point of view of UCG. We discuss some geological literature available for these areas. Coming to the rock mechanics perspectives, during UCG the rock temperature is considerable high. At this temperature, most empirical models of rock mechanics may not be applied. In this situation, the challenges for numerical modelling of UCG sites increases manifold. We discuss some of the important modelling geomechanical issues related to UCG in India.

1. Introduction

Stringent climate targets are likely to change the way of coal usage in the near and long term. With an view to strengthen India's energy security, an effort must be made to diversify coal usage while also finding potential mechanisms to reduce our natural gas imports. This becomes even more relevant for India as 55% of the commercial energy comes from coal and lignite. This trend is likely to continue for the years to come as per various modelling studies and expert elicitations [1, 2]. In this state of affairs, coal gasification may become a useful technology for India.

Surface and underground coal gasification both are at the forefront of clean coal technologies. It is demonstrated that coal reacts with some oxidants like oxygen or air and sometimes steam at elevated temperature and pressure in a reactor to release a product synthetic gas (syngas), which is a mixture of carbon monoxide, hydrogen, methane, carbon dioxide, nitrogen, hydrogen sulfide and other trace gases. The product syngas when used in an Integrated Gasification Combined Cycle (IGCC) turbine, provides significantly high efficiencies for power generation. Capture and storage of carbon dioxide, which is another topic of major research interest throughout the globe, is amenable to gasification of coal. The essential concept of underground coal gasification (UCG) also known as in-situ gasification is to develop an underground gasifier. Like surface gasifiers, UCG process also involves simultaneously existence of oxidation, reduction and distillation zones in the underground gasifier.

Majority of the UCG trials throughout the globe has been attempted using the linked vertical wells method in flat or gently dipping coal seams [3]. In this method, a pair of boreholes called injection and



production wells are drilled from the surface into the horizontal coal seams. Linking is established between the two boreholes through the coal seam in order to ease the flow of gases from the injection well to the gasification zone and also from the combustion zone to the production well. The coal is ignited at the bottom of the injection well. Gasifying agents such as air or enriched air or oxygen and steam are injected into the coal seam through the injection well to support ignition followed by gasification of coal.

Energy demand of India is increasing continuously and being the major fossil fuel, coal plays an important role in the energy sector. India is the third largest producer of the coal in the world. The geological resources of coal in India is reported as more than 300 billion tonnes upto a depth of 1200m as on 01.04.2015 out of which proved reserve has been reported as 125.90 billion tonne [4]. The coals are of sub-bituminous to bituminous rank and in some places lignite, having high ash content and low calorific value, which makes it uneconomical to mine from such a greater depth. In India, UCG was first taken up in the mid 1980's. The Government of India has already indicated production of syngas obtained through UCG as "Approved End Use". Hence, in addition to the implementation of a pilot UCG projects, two coal blocks namely Kaitha in Ramgarh coalfield and Thesgora 'C' in Pench-Kanhan valley coalfields were identified for commercial development.

This paper discusses some of the geological and rock mechanics perspectives related to UCG projects in India

2. Rock Mechanics Perspectives

UCG processes are likely to lead in deformation of 60% strata (if we assume a coal with 40% ash content). In conventional mining, all the material would be extracted, but in UCG this reduces by a margin of 40%. By removal of excess material in conventional mining processes, there is considerable deformation in the strata (Figure 1). This shows an advantage in terms of the residual ash and also in the rock mechanics perspectives. However, in case proper geologic controls are not in place, there is a fear of subsidence. Thus, it is imperative to predict the amount of displacement faced by the rock strata [5]. Modeling can easily indicate the amount of physical displacement of the strata but it may not be useful in defining the geo-engineering characteristics of the rocks. Since, high temperature causes drastic variations in the rock properties; the modeling of UCG is considerably difficult.

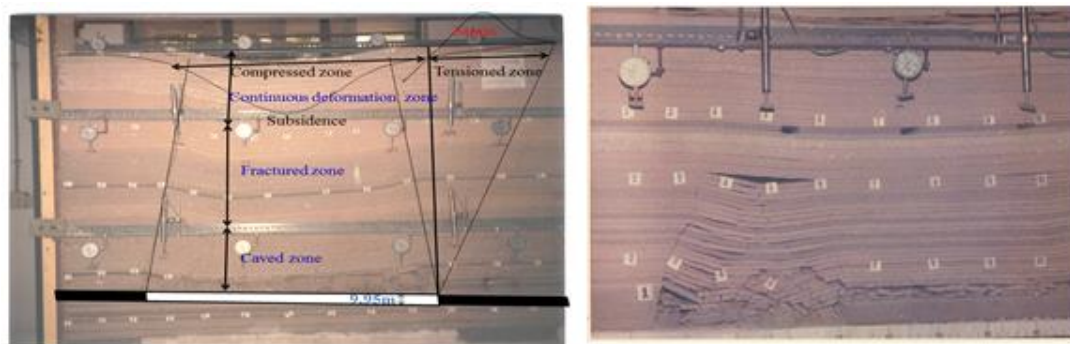


Figure 1. Simulation of deformation and displacement of rock strata using rock-mechanics based computational techniques (after [6])

Both physical and numerical models can be utilized to understand the strata mechanics patterns during excavation of caverns [6, 7]. In such studies, it has been found that the depth as well as the width of the tunnel/cavern has significant impacts on the strata mechanics (Figure 2), in addition to the overlying rock strata properties (Figure 3). Mathematical modelling in such cases is a convenient way to model rock mechanics during mining operations. The results of such models can be then compared to empirical results to ensure that the developed models suit the purpose of our studies, and can be constantly improved taking field considerations into account. Thus, we zero-in on the suitable models

for simulating different cases of mining operations. A number of such empirical rock failure criteria have been developed, an overview of which may be found in Sheorey [8]. Researchers have suggested that the results found in empirical studies, may be significantly different from established international models. For instance, Sheorey et al [9] have pointed out that there are considerable variations in the field studies carried out for Indian coalfields, as compared to the Subsidence Engineers Handbook, UK. They have also demonstrated that difference exist in the cases of extraction below unfractured or uncaved rock and below pre-existing caved goaf(s). Some studies have been developed for estimating subsidence behaviour in UCG [10, 11]. Geophysical monitoring studies have also been suggested for UCG [12].

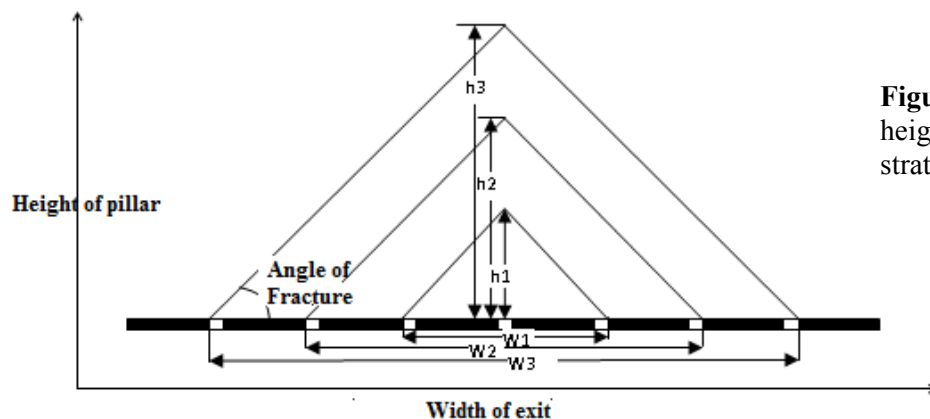


Figure 2. Effect of height and width on strata mechanics

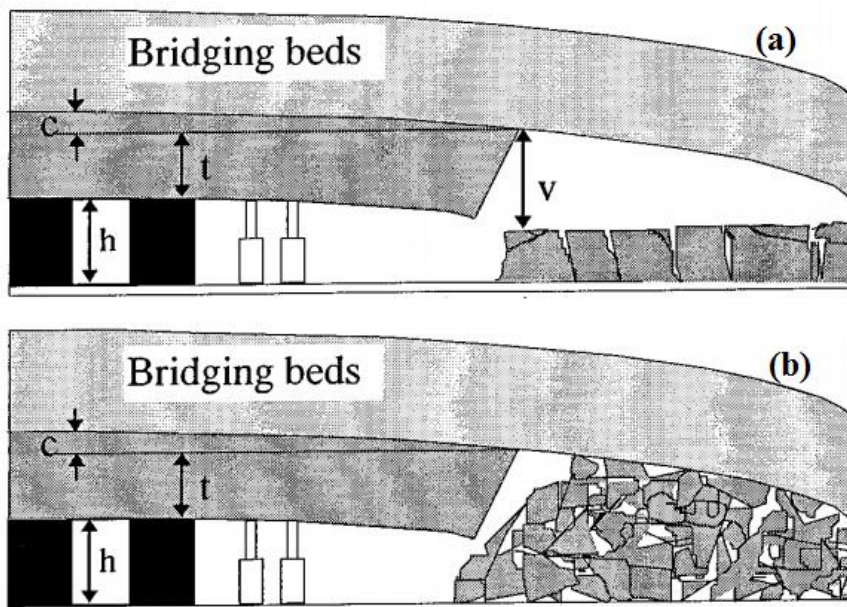


Figure 3. Effect of rock properties for the case of (a) strong and (b) weak overlying rock strata ([6])

In fact, presence of massive rock and complex geo-mining conditions induce large complexities into modelling rock mechanics problems. This raises the imperative for some simplifications, so far as possible. In a physical model, the process of assimilating the equivalence of strength by constantly incorporating the condition and equality of the event is inherently contained. The numerical method shows the methods that are direct attempts to solve fundamental differential equations, integral equations, or the principle of change. With advances in computational power, mathematical models for rock mechanics problems are becoming significantly popular, and a number of recent works have come up in this area [13]. Analysis of results obtained from efficient modelling can greatly reduce the costs and provides complete information about the distortion of rock strata. Most of the information in geotechnical models is extracted from the coal core obtained from the boreholes. These cores are

tested for mechanical strength in the laboratory. The results from small core samples are translated into the results for the entire rock mass. However, in many cases, these results do not match, especially in case of massive rocks. To avoid this uncertainty, modelling results are compared with the results of empirical formulation.

As stated, for the modeling of UCG, defining physical and engineering properties of large rocks becomes quite complicated as the high temperature has significant impact on the physical and engineering properties of rocks. To our knowledge, no integrated study so far exists, which estimates the changes in rock properties in such high temperatures for Indian coalfields. Luo and Wang [14] have estimated the impacts of high temperature on the properties of mudstone in the UCG process. Yu et al [15] have also studied the development of micro-pores in coal structure with temperature. Liu and Xu [16] have estimated the threshold temperatures for change in strength for granite using longitudinal wave velocity. Similar studies should be carried out for Indian coalfields for assessing feasibility of UCG in India. In fact, Sirdesai et al [17] have carried out a computational study using COMSOL Multiphysics software to understand subsidence behaviour during UCG. They have concluded that cavities of width less than 100 m cause lower subsidence. This study can further be improved with addition of geological constraints such as presence of groundwater and other features. Figure 4 shows the effect of depth and cavity width on the degree of subsidence.

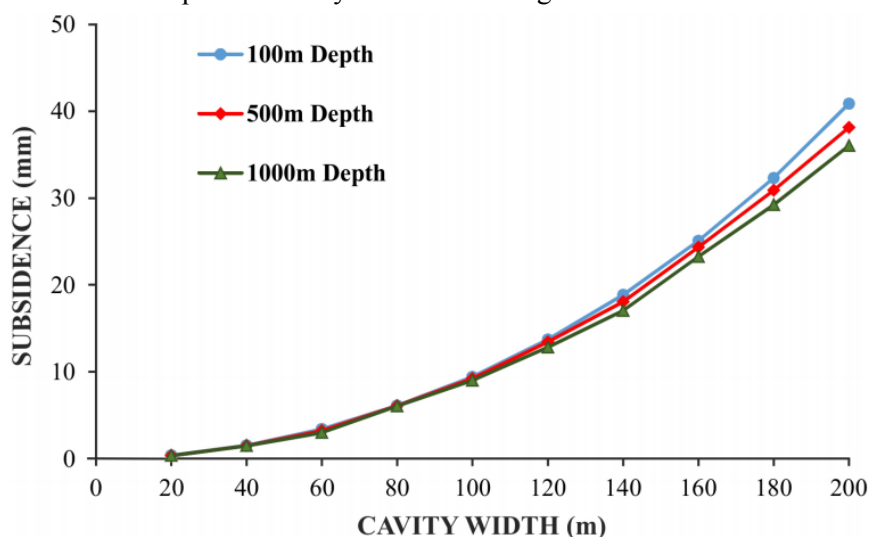


Figure 4. Effect of cavity width and depth on subsidence. Source: Sirdesai et al [17]. Reproduced with permission from authors

In general, there is no need to account for temperature variation in conventional mining processes. However, UCG is an exception to this as the rock temperature may reach in excess of 1200 °C. This temperature can be maintained after a long period of time after combustion of coal and continuously during gasification. The deformation process of rock at high temperatures depends on contact with mineral structure and deposited grain [18]. At high temperatures, properties are affected majorly due to the deposited particles in the rocks such as soil, clay, sand etc. Quartz-Feldspars minerals present in the rocks affect the rock properties [19]. Malkowski [18] has also demonstrated that various rock respond differently to high temperature based on their depositional features.

3. Geological perspectives

In the past, our group has focussed on UCG in Cambay Basin (Gujarat), Barmer-Sanchor (Rajasthan) and north-eastern coalfields. Chemical analysis of lignites from Gujarat show that fixed carbon content is between 30-45%. Further, it was found through thermo-gravimetric analysis (TGA) that Umarsar lignite is the most reactive in this region, followed by lignites from Vastan, Panandhro, Valia and Bhavnagar [20]. Syngas modelling was also carried out for lignites from Kapurdi mine in Rajasthan. These are coals with high moisture and low sulphur content. The study suggests that at 20% oxygen concentration, some amount of coal is left unreacted while at 60% concentration, the CO₂ formation is

higher than CO [21]. We also performed an integrated project relating to the feasibility of UCG in the northeastern India, the full report of which may be found in [22].

Some other studies with relevance to UCG may be discussed here. Daggupatti et al [23] have shown using modelling that in lignites, that bypassing of oxygen may occur in cases where the cavity in the forward direction closely approaches the production well. Prabhakar et al [24] have performed modelling studies for sub-bituminous coal and concluded that combined kinetics and heat transfer model is more effective in prediction gasification characteristics. Singh et al [25] have predicted that for heat affected coals from the Jharia coalfield, changes in properties are similar for in-situ or laboratory carbonation. Mukherjee and Srivastava [26] concluded that when heated in presence of air, the stretching, bending bands disappear. A highlight of some other studies focussing on geology and petrography in Cambay Basin, Barmer-Sanchor and Northeastern coalfields is shown in Table 1.

Reference	Methodology/Assumptions	Results
Gujarat		
Singh et al [27] (<i>Petrological and chemical studies on Vastan lignites in Gujarat</i>)	<ul style="list-style-type: none"> • Samples from open mines were collected using pillar sampling • Leitz Orthoplan Pol microscope with an Photoautomat MPS 45 control module was used for microscopic study • Particle size for microscopic analysis was kept at 18 mesh size • 70 mesh size particle size was used for proximate and ultimate analysis 	<ul style="list-style-type: none"> • Out of huminites, liptinite and inertinite maceral groups, huminites are in abundance • Fuginites occur individually and in clusters • Lignites are reported with high moisture, moderately high volatile matter and varying ash content. • Average sulphur content is 1.59% • Sulphur content is more for lower seams • Sulphur content increases with increase in ash content
Singh et al [28] (<i>Petrological and chemical studies on Rajpardi lignites in Bharuch district in Gujarat</i>)	<ul style="list-style-type: none"> • The samples were collected from Amod mine in Jhadagia area in Bharuch • Pillar method of sampling as used • Microscope with an Photoautomat MPS 45 control module was used for microscopic study • Particle size for microscopic analysis was kept at 18 mesh size • 70 mesh size particle size was used for proximate and ultimate analysis 	<ul style="list-style-type: none"> • Huminites were in abundance ranging from 68.9 to 92.6% in vol basis • Telohuminite and detrohuminite are a majority within humnities • Liptinites ranged from 1% to 6.5% in vol. basis • Mineral matter content showed large variation • Lignite was identified with have high volatile matter and hydrogen content
Rao et al [29] (<i>Palynostratigraphy and study of depositional environment of Vastan mine, Gujarat</i>)	<ul style="list-style-type: none"> • 33 samples were collected of which 31 were finally used • Palynofossils were recovered from these samples • Samples were treated with 	<ul style="list-style-type: none"> • 86 genera and 105 species of algal remains were identified • 7 genera and 8 species of fungal remains were

	HCl, HNO ₃ and HF and later with 5% KOH	<p>identified</p> <ul style="list-style-type: none"> • 57 genera and 73 species of angiosperms remains were identified • Three cenozoones zones namely Proxapertites spp. Cenozoone, Operculodinium centrocarpum Cenozoone and Spinizonocolpites spp. Cenozoone were identified on the basis of percentage frequency of palynomorphs
Mallick et al [30] (<i>Pyrolytic and Spectroscopic studies on Eocene resin in Vastan lignite</i>)	<ul style="list-style-type: none"> • FTIR spectroscopic analyses were done in transmission mode on a Nicolet MANGA 550 model running OMNIC software • The sample was flash pyrolysed at 600°C for 20 sec by a CDS analytical pyroprobe • Pyrolysis chamber was kept at a constant 300°C • Curie point pyrolysis was conducted in a Curie point pyrolyser 	<ul style="list-style-type: none"> • Fossil resin contains 78% of C, 10% of hydrogen by weight • Fossil resins were found to be rich in aliphatic compounds from the FTIR data • Cadalene based C-15 bicyclic sesquiterpenoids were found in abundance • Upon pyrolytic study, Vastan resin are identified as class 2 resin
Rajasthan		
Singh et al [31] (<i>Thermal maturity and hydrocarbon potential studies on lignites of Bikaner-Nagaur basin</i>)	<ul style="list-style-type: none"> • Sampling was done using pillar coal sampling technique • Sample was prepared at 18 mesh size for petrographic analysis and 72 mesh size for proximate and ultimate analysis • Maceral analysis was conducted at BHU, using a Leitz Orthoplan Pol Microscope • Hydrocarbon potential determination was done using Rock Eval-6 pyrolysis 	<ul style="list-style-type: none"> • Lignite was found to be rich in huminite macerals (86.3% on an avg in mmf basis) • It majorly contains kerogen organic matter • Liptinite content was 4.4% on an average • Mineral matter shows variation • Lignites have high volatile matter content (54.4% to 60% in daf basis)
Mukherjee et al [32] (<i>Study of physical, chemical and petrographic properties of Kapurdi lignite in Barmer Basin</i>)	<ul style="list-style-type: none"> • Study was conducted on Kapurdi lignites deposited in Barmer Basin, Rajasthan. 	<ul style="list-style-type: none"> • Vicker micro-hardness parameter values varied between 20 to 22 kg/mm² • Coal samples were high ranked with low ash content • Among macerals, huminites

		were the major constituent
North Eastern Coals		
Singh et al [33] (<i>Petrographic and geochemical studies on coals in Tiru Valley in Nagaland</i>)	<ul style="list-style-type: none"> • Sampling was done using pillar coal sampling technique • Sample was reduced to 18 mesh size for petrographic analysis and 70 mesh size for proximate analysis • Leitz Orthoplan Pol microscope attached with a wild Photoautomat MPS 45 control module was used for microscopic study 	<ul style="list-style-type: none"> • Rank of the coal varied between sub-bituminous and bituminous-D in rank • Vitrinite constitutes 98% of the total maceral content • Volatile matter in daf basis ranged from 34% to 48% in daf basis • Coal is high on sulphur content that leads to pyrite formation
Sahoo et al [34] (<i>Geochemical study of coal mine discharge in Jaintia Hills coalfields</i>)	<ul style="list-style-type: none"> • Water samples from mine discharge, dug wells and AMD affected streams were collected and filtered • Sample was treated with acid (4% HCl for Fe^{+2} and HNO_3 for other metals) • Acid treated sample is stored in PP bottles at 4°C • PHREEQC version 2.15 was used to model the geochemical aspects • Ion selective electrode (ORION 5 star) was used for the determination of pH 	<ul style="list-style-type: none"> • pH of drainage from mine is found to be highly acidic (1.6-4.8) • SO_4^{2-} found in major quantities in mine discharge • In dug-wells, HCO_3^- was the most dominant radicle • Iron and aluminium were the most found dissolved metals in mine drainage
Saikia et al [35] (<i>Geochemical and nano - mineralogical analysis of coal and its mining by-products, in Assam</i>)	<ul style="list-style-type: none"> • Samples were taken from Ledo and Tikak collieries • Standard (ASTMD2234M, 2010) sampling method was used for coal sampling • Grab samples from the overburden were made from the two sites. • Two fly ash samples were taken at an interval of 24 hours from an electrostatic precipitator at a PC power plant at Nagaon 	<ul style="list-style-type: none"> • Coals had high organic sulphur content • Results from ultimate analysis reveal more than 10% carbon content in overburden • Vitrinite takes up the major portion of the total organic content of coal (95% in mmf basis) • Overburden also is found to be rich in vitrinite (10% -15% in mmf basis)

4. Conclusions

Geological parameters have significant impacts on UCG deployment in a region. A very brief review of the geological parameters in lignite-fields from Rajasthan and Gujarat, along with coalfields from North-eastern India has been carried out. Some previously published results relating to UCG deployment in Rajasthan and Gujarat indicate their high feasibility in such reasons. As regards to rock mechanics perspectives, development of new models is extremely necessary, since the present computational models developed for Indian coal mines are likely to be proven ineffective at

temperatures in excess of 1200 °C. New empirical models need to supplement and improve newly initiated computational modelling techniques for Indian coalfields at such high temperatures. A framework for such a model is depicted in Figure 5 and may hold scope for future developments in UCG.

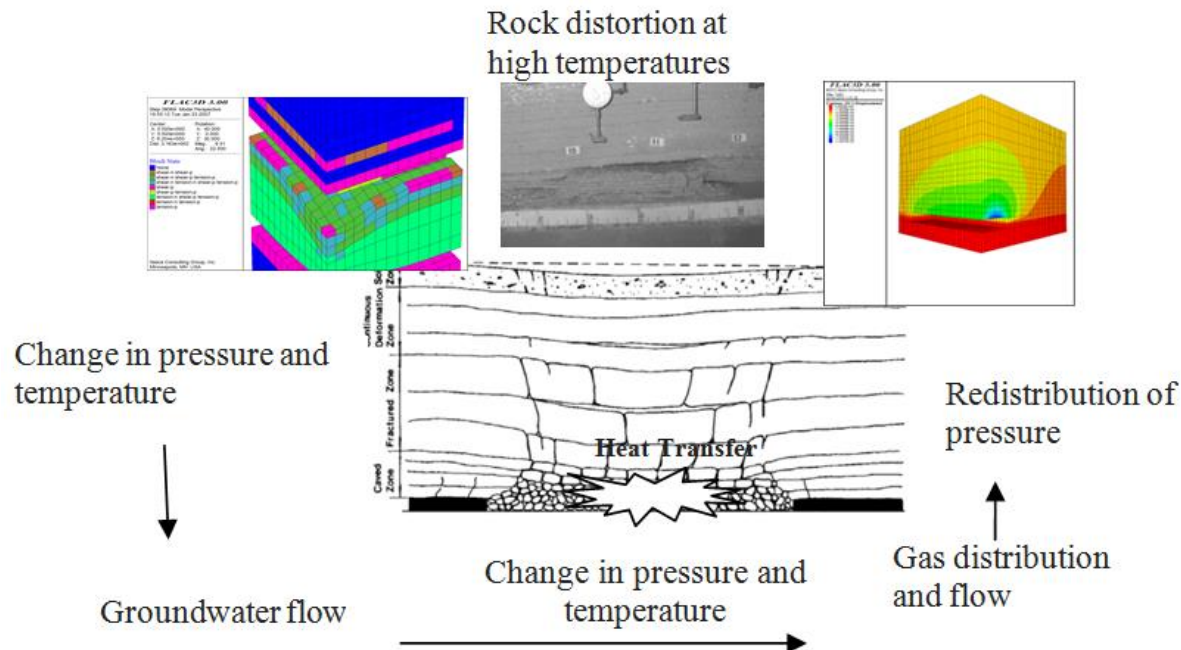


Figure 5. Framework for UCG model development

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