How the Engineering Properties of Rock Types are Influenced by their Geological Formation

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Abstract:

This report covers the theory behind how different geologically formed rocks have different properties from an engineering perspective. It explores the distinct characteristics of sedimentary, igneous and metamorphic rocks, emphasising how their geological historic formation affects their engineering properties. The analysis bridges the gap between laboratory-scale testing of small rock specimens and the real-world implications of rock mass properties in large scale civil engineering contexts. Using both literature and case study material, various properties - elasticity, porosity, density, wave velocity, strength and mineral composition - of these rocks are shown to affect the outcome of such civil engineering projects, and therefore show that critical planning is needed to determine which rock types are most suitable in different contexts.

I. Introduction

The understanding of rock formations when planning and implementing civil engineering projects is pivotal to the integrity of any building via its foundations. Rocks will be classified into three categories throughout this report; Sedimentary; Igneous; Metamorphic. The characteristics of these can be examined and compared to one another with reference to laboratory tested samples to achieve a greater understanding of how these rock formations affect large scale engineering infrastructure built into these rocks.

The report will begin by going through the formations of these three types of rock over time and will then outline their theoretical and established engineering properties. An analysis of laboratory tested results will be aligned with the established theory and conclusions are made about how the different formations affect the decision making and implementation for various types of construction projects.

II. Geological Overview of Rock Types

When looking at each major formation of rock separately, specific qualities and traits can be realized. Rocks found on the earth's surface can be classified as sedimentary and crystalline, by 66 percent and 34 percent respectively [5]. One quarter of crystalline rocks are found to be igneous [5]. To best understand the properties of them, and as aforementioned, it is most useful to classify them into three major groups, Sedimentary, igneous and metamorphic:

A. Sedimentary rocks:

Sediments are formed due to erosion and are deposited by air or water. The deposition, erosion and speed of transport all affect the grain size of the resulting sedimentary rock. The clastic types of sedimentary rocks can be broadly split by grain side:

- Coarse grained: conglomerate, breccia
- Medium grained: sandstones
- Fine grained: siltstone, clays

The non-clastic typoes of sedimentary rocks can be split into:

- Carbonates: limestones
- Non-carbonates: flint, ironstone, salt et al

A visual difference can be seen in the grain sizes when comparing cross-sections of three different sedimentary rocks - see Figure 1.

Figure 1. *Top to bottom.* First column shows example sedimentary grains of Conglomerate, Sandstone, Siltstone; Second column shows intrusive and extrusive igneous examples, Granite and Obsidian; Third column shows foliated and non-foliated metamorphic examples, Slate and Marble. [1]

B. Igneous rocks:

Igneous rocks form from the solidification of molten magma. Intrusive igneous cools more slowly below the earths surface to produce coarser rock, whilst extrusive igneous is made from the rapid cooling of magma on the earths surface. Intrusive igneous rocks are classified [7] as such:

- Batholith (rock mass covering an area >100km)
- Stock (rock mass covering an area <100km)
- Laccolith (s-shape curved intrusions between sedimentary layers)
- Sill (flat intrusions between sedimentary layers)
- Dike (sheet intrusion into a crack of a pre-existing rock)

The minerals found in extrusive igneous rocks are much finer grained due to the rapid cooling and crystallisation of the lava. This makes it harder to classify extrusive igneous rocks. Examples can be found in Figure 2 below.

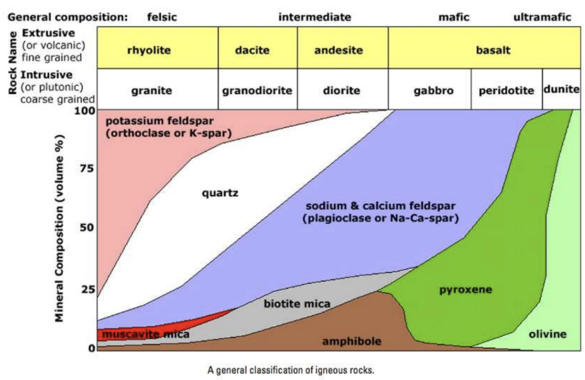

Figure 2. *Top to bottom.* Types of intrusive and extrusive rocks, classified by texture, colour and mineral composition.[10]

C. Metamorphic rocks:

Metamorphic rocks result from the transformation of existing rock types under high pressure and temperature, without melting. Foliated metamorphic rocks are characterised [20] by their layered appearance and include:

- Slate (metamorphosed from shale; fine grained)
- Schist (metamorphosed from shale or mudstone; medium to coarse grained)
- Gneiss (metamorphism of multiple highly-graded rocks; alternating bands of light and dark materials)

Non-foliated metamorphic rocks are typically formed where uniform pressure is applied and include [20]:

- Marble (metamorphosed from limestone; characterised by recrystallized calcite crystals)
- Quartzile (metamorphosed from sandstone; quartz grains are welded together with additional silica)
- Hornfels (metamorphism of fine grained rocks; elongated minerals form from differently angled pressures)

III. Engineering Properties of Rocks

When looking at the engineering properties of the different rock formations listed in II, various aspects can be explored [24]:

- Elasticity - the lack of deformation per applied stress until failure
- Porosity - the ratio of pore (empty) volume to the total volume of rock
- Density - the total mass per total volume of rock
- Wave Velocity - the speed at which seismic waves travel through rock formations
- Strength - the amount of direct force that can be applied to a rock without failure
- Mineral composition - the makeup of the rock in terms of one of more minerals

The **elastic** properties of rocks, however, can be ignored [22] when it comes to practical applications as the elastic moduli found in the laboratory are not often the ones used in engineering analysis.

Porosity generally declines with higher pressures or depths [17]. Figure 3 shows an example of this trend for sandstone. Porosity generally decreases with temperatures up to 200ºC, before increasing with higher temperatures, as found by an experiment where two marbles and three limestones were heated to 500ºC [23].

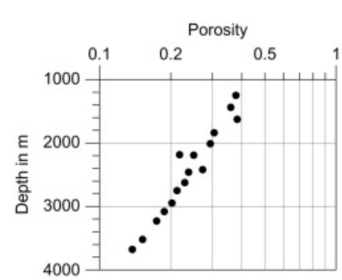

Figure 3. Plot of log(porosity) vs depth for sandstone [17]

Due to the decreasing nature of porosity with depth, the **density** can be said to increase with increasing depths.

The **wave velocity** is important for understanding how different rock types react to seismic waves. This is more relevant in regions of seismic significance, but it is also useful for showing the strength and durability of different rock types. Figure 4 shows the ranges of velocities that P and S waves travel through the rock types listed.

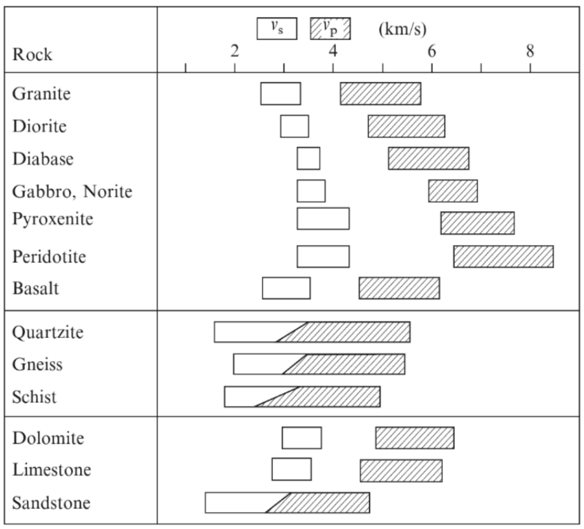

Figure 4. Range of P and S wave velocities for different Igneous, Metamorphic, and Sedimentary rocks [24] and [16].

The **strength** of different rock types can more directly be assessed using different methods. A point load test applies a compressive load until a rock breaks in tension. The Schmidt hammer test can be employed as a non-destructive way of testing strength. It can be seen how the *Schmidt hardness* increases linearly with uniaxial compressive strength for sedimentary type rocks in Figure 5.

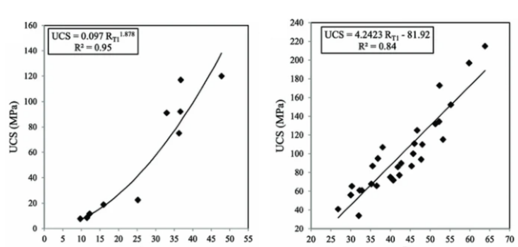

Figure 5. the general relationships between R and UCS for sedimentary (left) and igneous (rocks) rocks where R is *the Schmidt hardness* and UCS is *the uniaxial compressive strength.* [12] and [16].

The Rock Mass Rating (RSR) is a classification of rocks in which a rock is divided into geological units and the UCS, Rock Quality Designation (RQD), joint spacing, joint condition, joint orientation and ground water condition are determined.

Figure 6 displays how the RSR classification of a rock affects construction when tunnelling or mining, in terms of its stand up time (how long the tunnel will stand without additional support) and roof span (width of tunnel).

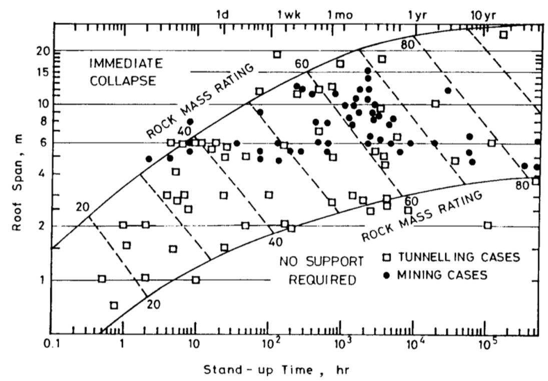

Figure 6. The stand up time vs roof span for different rock classes seen in [21]. Figure taken from [18].

The **mineral composition** of a rocks can widely dictate the properties that it holds. A study done by the American Rocks Mechanics Association [14] created a model comparing the properties of sedimentary rocks with varying degrees of dolomite, clay, plagioclase and quartz. The results in respect to the quartz content and the measured compressive strength to strain is seen in Figure 7.

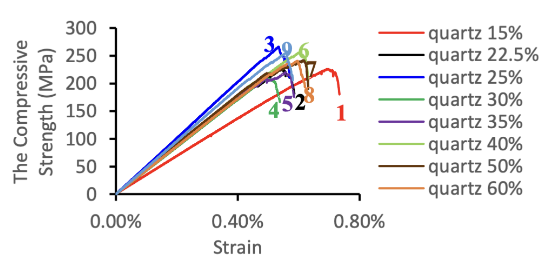

Figure 7. The results of the strain/UCS from the simulation [14].

A. Correlations between Properties

The point load index is a direct measurement of the strength of a rock type. Figure 8 shows how the Point load index is much higher at a low porosity and much lower at a high porosity.

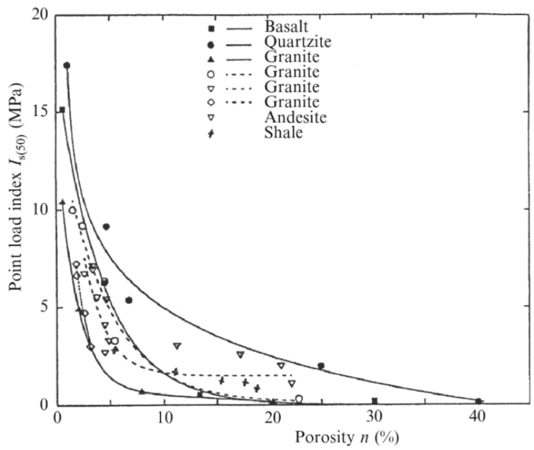

Figure 8. Variation between point load index and porosity for various crystalline rocks [24].

IV. Summary of Engineering Properties

1) Sedimentary Rocks:

- Porosity in sedimentary rocks often varies, influencing their strength and durability. It typically decreases with depth and under high pressure.
- The strength of sedimentary rocks can be assessed using tests like the Point Load Test, with strength influenced by porosity. The Schmidt hardness is noted to increase linearly with uniaxial compressive strength.
- Mineral composition, including elements like dolomite, clay, plagioclase, and quartz, significantly affects the properties of sedimentary rocks.

2) Igneous Rocks:

- These rocks generally exhibit high strength due to their crystalline structure and mineral composition, making them suitable for heavy-duty construction.
- The specific minerals in igneous rocks, formed from cooled magma or lava, contribute to their unique engineering properties.
- The high strength and density of igneous rocks, in general, is shown by the relative high speeds of P and S waves when travelling through igneous rocks.

3) Metamorphic Rocks:

- The complex mineral composition of these rocks dictates their engineering properties and suitability for various applications.
- The Rock Mass Rating (RMR) classification is crucial in understanding the stability and suitability of metamorphic rocks in construction, especially for tunneling and mining.

V. Case Studies and Engineering Applications

A. Tynemouth railway, North East England

During a departmental field trip to Tynemouth, bedding planes along sandstone below a railway track were observed. It was noted how cracks, likely caused by tectonic activity, allow for vegetation to grow through the sedimentary planes, adding stress between planes. A slip plane in the direction of the rock was spotted and it was established it would be unsafe to build on the *slipping* side. However measures could be taken to minimise the risk of rockfalls by inserting steel bars into the rock, creating intended tension between the planes. This was evident in the rock under the railway.

B. Methods of excavation of sedimentary rock

A case study from Malaysia on the assessment of sedimentary rock mass rippability (the ease with which soil or rock can be excavated) for a new spillway dam project exemplifies the importance of understanding rock properties in civil engineering. This project utilized seismic refraction surveys - an image can be seen of this in Figure 9 - to evaluate the characteristics of the sedimentary rock formation, crucial for determining the feasibility and approach for the construction. The study is a clear example of how geological properties of rocks directly influence engineering decisions and project outcomes [3].

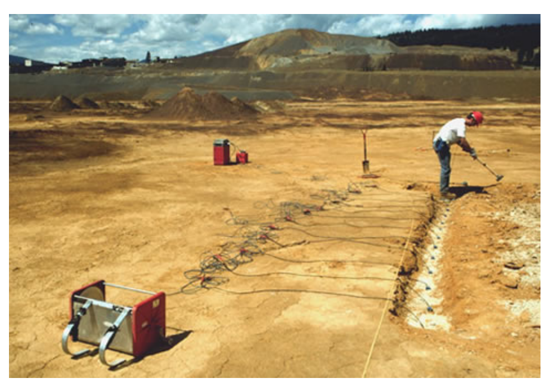

Figure 9. A depiction of a seismic refraction surveying setup using 12 geophones (seismic waves detectors) and a worker using a hammer (to generate the waves through the rock) [19].

C. Fenhe River Diversion Project

The case study [9] from the Fenhe River Water Diversion Project in Shanxi Province, China, demonstrates the complex challenges faced during tunnel construction in geologically diverse settings. This project, dealing with a variety of rock types, including igneous formations, required extensive geological and geotechnical analyses. The use of advanced rock mechanics and finite element modeling was crucial to understanding and addressing the stresses and displacements in the rock during the tunnel construction.

The study illustrates the intricacies of working with different rock types, particularly igneous rocks, in large-scale engineering projects. It emphasizes the necessity of thorough planning and application of appropriate construction techniques in response to complex geological conditions. This case study serves as a prime example of the intricate relationship between geological formations and engineering strategies in civil engineering projects.

D. Durability and Weathering of Metamorphic Rocks of Sri Lanka

In a significant study [11] focused on the metamorphic rocks of Sri Lanka, researchers delved into understanding the durability and weathering of these rocks under tropical conditions. This case study is pivotal in assessing the suitability of these rocks for various construction and engineering applications. Sri Lanka's geological makeup predominantly consists of Precambrian metamorphic rocks, forming about 90 percent. The study employed a series of physical, chemical, mechanical, and optical tests to evaluate the weathering rate and durability of these rocks. Notably, micropetrographic indices and rock durability indices in static and dynamic states were used as critical indicators. Tests such as the Point Load Index Test, Modified Aggregate Impact Value Test, Specific Gravity Test, and others were carried out to determine the suitability of these rocks for construction purposes. The research underscores the need for thorough quality analysis of metamorphic rocks before their utilization in construction projects, especially in tropical environments like Sri Lanka.

The key takeaways from the findings [11] are:

- **Understanding Rock Properties**: Detailed knowledge of the physical and mechanical properties of rocks is essential for predicting their behavior and suitability in construction.
- **Adapting to Environmental Conditions**: The study suggests that environmental factors significantly influence the durability and service life of metamorphic rocks, necessitating adaptive construction strategies.
- **Interdisciplinary Research Approaches**: The interplay of factors affecting these rocks highlights the complexity of natural systems, advocating for interdisciplinary research to fully comprehend and utilize these materials effectively.

VI. Discussion

A. Geological Formation Suitability for Applications

The geological formation of sedimentary rocks as discussed in section II and looked at in section III exhibit varied densities and porosities. In particular, fine grained and soluble sedimentary rocks should be considered very carefully by geotechnical engineers [15].

Igneous rocks tend to be much harder. Basalt, which is mafic (i.e. containing more minerals and less silica than felsic igneous rock), and intrusive rocks like granite, are some of the most useful building materials. Granite is very dense and therefore has a low permeability whilst basalt is rich in magnesium, iron and calcium oxides, giving it a high melting point and good resistance to chemically active environments. [2]

Metamorphic rocks have a large variability of qualities and strengths (see figure 4). Slate is a suitable roofing material, due to its ability to split into thin, yet hard, sheets. Marble is widely used aesthetically for interior purposes, for its unique appearance. Quartzite and gneiss, however, are widely used for construction purposes due to their hardness and resistance to abrasion [13]

B. Engineering Challenges and Solutions

Building on soluble rocks, like limestone, can pose a major risk of subsidence. Geotechnical engineers use surveying measures and drilling to assess the ground and rock conditions. Techniques such as grouting and underpinning can be used to stabilize the ground [4].

When excavating and drilling down into rock, for example if forming foundations, the relative hardness and density of igneous rock poses a challenge to construction, requiring heavy machinery to enable building on such rock which ultimately makes for stronger foundations.

As mentioned earlier in this section, the variability in strengths of metamorphic rocks mean that engineers typically need to test the quality and strength of prospective working rock, using non-destructive methods such as the use of ultrasonic equipment (see [6] for more detail), instead of relying on laboratory tested samples.

The case studies in V describe how many practices are employed in order to assess the rock that is either used for the construction of a tunnel, for example, or existing rock that a structure is built on or in. Sometimes, as seen in the field trip to Tynemouth, a lot can be deduced from a simple visual analysis and understanding of rock formations. For more in depth assessments, many tests can be performed, mainly to analyse strength but also the affect of seismic waves, which is indeed important in regions with enhanced seismic activity.

C. Environmental Considerations

The construction industry is increasingly using recycled rocks - as opposed to new quarrying ventures - to reduce the environmental impacts of work. However, measures can be taken when quarrying to reduce, recover and reuse the waste on-site (as it is found that 30-80 percent of quarrying volume ends up as waste; Norway and Italy, 2017 [8]).

D. Historical and Modern Applications

The use of rocks throughout historical architecture can be observed to give an understanding of previous construction methods and material selection, as well as show the evolution of technology in rock extraction and construction. Limestone and sandstone are two examples of rocks, of sedimentary formation, that were widely used throughout historical builds, due to their ease of quarrying and shaping. In the modern landscape, the widespread use of concrete (mixed with various rock aggregates) has taken over much of these previously used construction materials, due to its superior versatility, ease of production and economic efficiency.

VII. Conclusion

This report has provided an in-depth exploration of the engineering properties of sedimentary, igneous, and metamorphic rocks, emphasizing how their geological formation influences their properties. From the porosity and density variations in sedimentary rocks to the hardness and chemical resistance of igneous rocks, and the diverse strengths and applications of metamorphic rocks, it is evident that geology plays a crucial role in civil engineering and construction.

The analysis has shown that sedimentary rocks like limestone and sandstone, historically favored for their work-ability and availability, are now complemented by the use of more versatile materials like concrete in modern construction. Igneous rocks, particularly granite and basalt, continue to be valued for their strength and durability, forming the backbone of many robust structures. Metamorphic rocks, with their aesthetic appeal and varied strength, find applications ranging from functional to decorative.

Engineering challenges arising from the properties of these rock types are addressed through advanced techniques and technologies. For instance, the risks associated with building on soluble sedimentary rocks are mitigated by thorough geotechnical assessments and stabilization techniques. The excavation challenges posed by the hardness of igneous rocks are overcome with modern machinery and drilling methods, ensuring strong and reliable foundations.

The environmental considerations of rock use in construction have led to an increasing focus on sustainable practices. The recycling of rock materials, responsible quarrying, and minimizing waste reflect the industry's shift towards more environmentally friendly approaches.

The historical and modern applications of these rocks have demonstrated the evolution of construction techniques and material selection. While traditional materials like limestone and sandstone were predominant in historical architecture, the use of concrete and advanced building materials has transformed the construction landscape.

The understanding of the properties in which different rock types hold is an essential part of any site investigation involving construction into or onto rock. The various tests in which the strength, porosity and seismic wave speed, in particular, are most useful to choosing a suitable rock type for a construction project.

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APPENDIX

[Structural geological mapping Exercise]:

ENGI 3311 - Geology for Engineers - PNH

MODULE ENGI 3311: GEOTECHNICS 3 – Geology for Engineers

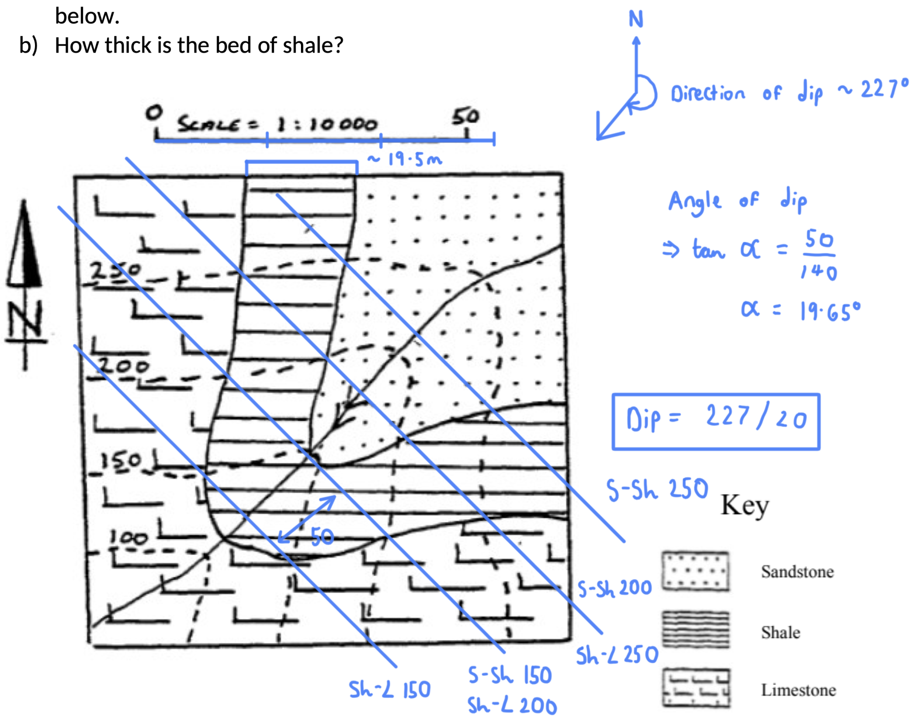
Michaelmas Term

Lectures 7-8 mapping exercises

We will be going through how to complete these exercises in in lectures 7 and 8. You will need to complete these exercises and attached them as an appendices to your coursework report.

Mapping exercise 1

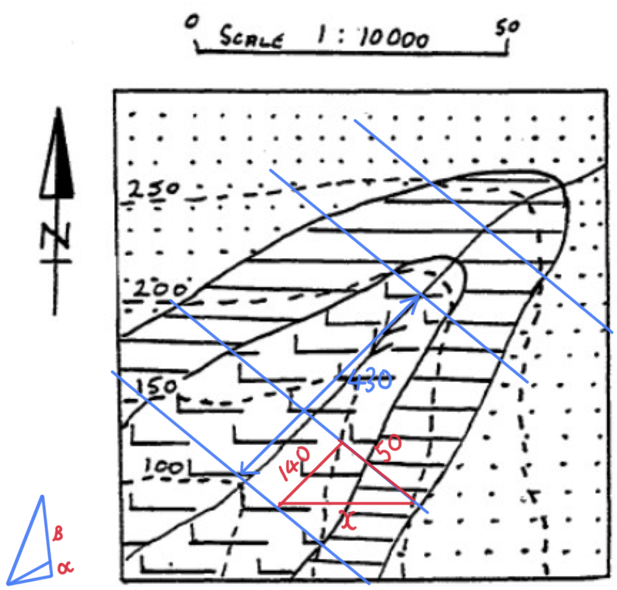
a) Estimate the direction and angle of dip for the strata shown on the map shown below.
b) How thick is the bed of shale?



$\cos 19.65° = \frac{\text{thickness}}{50}$; thickness = 47m

Mapping Exercise 2

a) Estimate the direction and angle of dip for the strata shown on the map shown below.
b) How thick is the bed of shale?

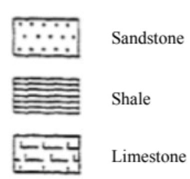


Direction of dip = 227°

$\tan \alpha = \frac{50}{430}$; $\alpha = 6.6°$

Dip = 227/7

Key



$\tan(\alpha + \beta) = \frac{50}{140}$

$\alpha + \beta = 19.65°$

$\beta = 19.65° - 6.6°$

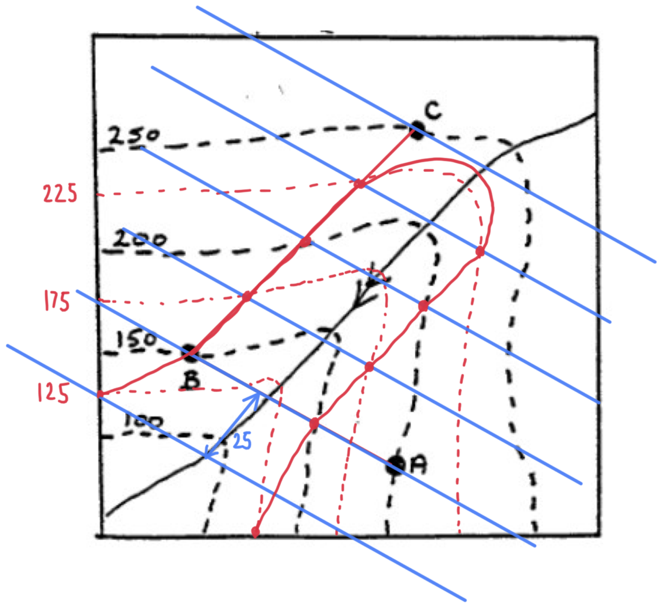
$= 13.05°$

$x = \sqrt{140^2 + 50^2} = 148.66$

$\sin 13.05 = \frac{\text{thickness}}{148.66}$; thickness = 33.6 m

Mapping Exercise 3 (three point problem)

Three boreholes, lettered A,B and C, have been sunk at the locations shown on the plan below. A Coal seam was revealed at the following depths: A=50, B=0m (outcrop) & C=25m. Deduce the dip and strike of the seam and show the outcrop pattern on the plan.



Direction of dip ~ 207°

Angle of dip:

$$\tan \alpha = \frac{25}{155}$$

$$\alpha = 9°$$

Dip = 207/9