An Analysis of the Structures and Geologic History of the Bree Creek Quadrangle

An in-depth review and analysis of the structures and geologic history of the Bree Creek region to understand the geomorphology and topography of the area.

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Abstract

The Bree Creek Quadrangle is the home of a series of events running all the way back from the early in the Paleozoic from the Ordovician, all the way to the Pliocene in the Cenozoic era. The area has a complex geologic history, and has been subject to various tectonic events and regimes, which resulted in the different structures seen along the quadrangle. The oldest units seen are Paleozoic in age, and have been subject to metamorphism, changing the composition of the rocks, where under compressional regimes folding was able to happen. A similar story carries on throughout the Paleocene and the Eocene in the Mesozoic, whereby compressional regimes continued, allowing for folding and faulting to occur of those units. It was likely that a transition into an extensional regime allowed for the rupture of the Gollum Ridge and Bree Creek faults, which was then followed by the deposition of the Pliocene unit, the youngest event in the Bree Creek Quadrangle. The different faults allow for the separation of four different fault blocks, where detailed analyses of the folding, faulting, stratigraphy, stresses can be done, which allow for the construction of the geologic and structural history of the Bree Creek region.

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1. Introduction

In the Bree Creek Quadrangle, a series of geologic structures in both the surface and sub-surface have had a direct impact and influence on how the geomorphology and topography in the area behaves. Tectonic events have led to the folding, tilting and faulting of the different units seen along the Bree Creek region, with the interactions of different contacts influencing the attitude of bedding. The Bree Creek area is an excellent example of how tectonic events influence geologic units, which then help influence the way topography and geomorphology define the area, and provide insight to how different geologic structures are formed.

Throughout majority of the Bree Creek region, a series of Paleocene to Eocene folded units are observed in both the surface and sub-surface, with a series of Paleozoic metamorphic units in the southeastern fault block that underwent two separate events of folding, with a Mesozoic igneous pluton that cuts through those units. Overlying the folded layers are a series of Miocene to Pliocene units that are largely planar, with a very small dip angle. The Bree Creek Quadrangle can be split up into four separate portions: the Western fault block; west of Mirkwood fault, the Central fault block; between the Mirkwood fault and the Gollum Ridge/Bree Creek fault, the Northeastern fault block; east of the Gollum Ridge fault and north of the North Bree Creek fault, and lastly the Southeastern fault block; south of the North Bree Creek fault and east of the Bree Creek fault. Three major unconformities can be recognised in this region, with a nonconformity between the Paleozoic to Mesozoic units and the Eocene units, an angular unconformity between the Eocene and Miocene units, and lastly a disconformity between the Eocene and Pliocene units.

In terms of topography and geomorphic features, the rivers and creeks tend to form within valleys, with a general northward downstream direction, with steeper valleys within the southeastern fault block where Weathertop is, and much gentler valleys across the rest of the region. The topography of the general area of the Bree Creek Quadrangle tends to consist of hills with relatively gentle slopes, with the highest elevation at hilltops being between 1932m above sea level and 1430m above sea level.

2. Stratigraphy

2.1 Bree Creek stratigraphic column

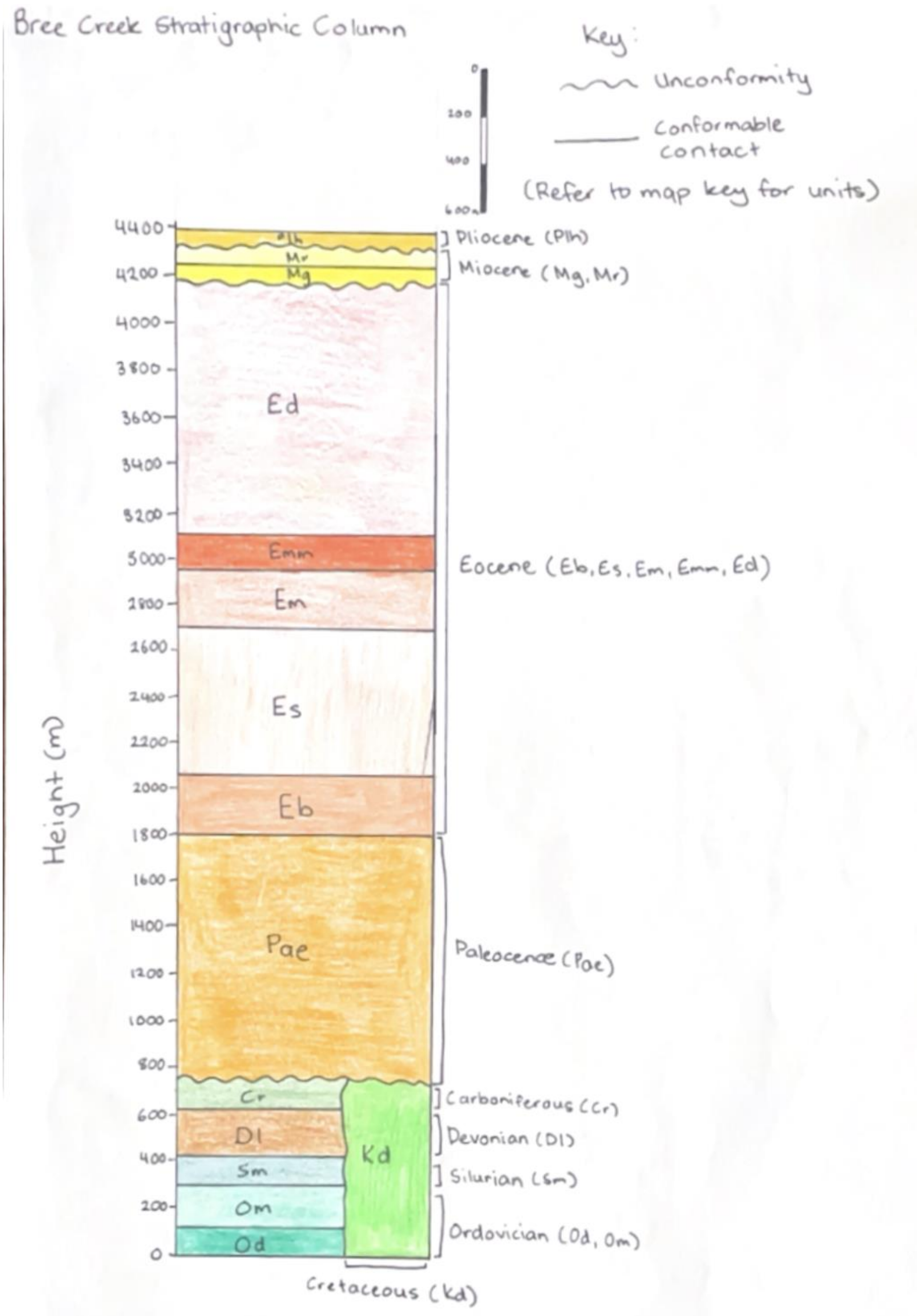


Fig. 2.1. A stratigraphic column of all the units that are observed and make up the Bree Creek Quadrangle. Early and oldest units are made up of Paleozoic metamorphic units, which are all cut by an igneous intrusion. Sitting on top of a nonconformity are a series of conformable Paleocene and Eocene sedimentary units. Overlying that is a series of sedimentary Miocene units, that sit directly on top of an angular unconformity, whereby the Eocene/Paleocene beds have undergone folding. The sequence is then capped with a Pliocene sandstone that sits on top of an angular unconformity in one specific region, and a disconformity in other areas where it can be observed.

2.2 Paleozoic and Mesozoic units

The oldest units seen at Bree Creek consist of a series of metamorphic units that are Paleozoic in age, starting with the Mt. Doom schist and Minas Tirith quartzite which are both of Ordovician age, deposited between 485 million and 443 million years ago. Overlying the Minas Tirith quartzite is the Moria slate, deposited in the Silurian between 443 million and 416 million years ago. The next unit consists of a Devonian unit, the Lonely Mountain quartzite, deposited between 419 million and 358 million years ago. The Paleozoic units are topped off by a Carboniferous unit known as the Rivendell marble, deposited between 358 million and 289 million years ago.

Cutting through all the metamorphic units is a Cretaceous igneous intrusion, the Dark Tower granodiorite, deposited 145 million and 66 million years ago. The original depositional environments of the protoliths are not clear due to the uncertainty of what the original rock types were, but because they are metamorphic, it can be inferred that the protoliths were buried (possibly due to faulting or subduction regimes?). There were likely other units overlying the metamorphic units and the igneous intrusion, but the metamorphic units were likely uplifted from depth with the faulting, then the younger units were eroded to expose the lower metamorphic units and igneous intrusion.

2.3 Paleocene and Eocene units

Overlying the Paleozoic metamorphic units are a series of sedimentary Cenozoic units, with a nonconformity between the metamorphic/igneous units, and the sedimentary units. Directly overlying the Rivendell marble is the Edoras formation, a formation of evaporites and nonmarine sediments, deposited during the Paleocene 66 million and 56 million years ago. The evaporites and nonmarine sediments are indicative of a basin/lake environment, with greater rates of evaporation than water input from precipitation or river influx, with nonmarine sediments implying an environment away from the coast.

Overlying the evaporites and nonmarine sediments are a series of Eocene units, indicative of transition from a fluvial lake environment to a marine environment, deposited between 56 million and 34 million years ago. The oldest Eocene unit is a Bree conglomerate, indicative of a high energy environment with heavy amounts of mixing, possibly in the tidal zone where wave energy is dominant. The Shire sandstone overlies that, implying a marine coastal environment, with a slight decrease in energy since the previous unit. The deposition of the Mirkwood shale overlies that, moving towards a very low energy environment, possibly anoxic (?), meaning either a drop in sea level or subsidence of the floor. The Misty Mountain limestone then overlies that, indicating a rise in energy from the previous unit, and possible a rise in sea level, or tectonic uplift. The Dimrill Dale chalk then overlies the limestone, another indication of a rise in sea level during the later period of the Eocene, or could be a deep-sea deposit that was later uplifted with tectonics, with lower energy and mixing rates associated with deposition.

2.4 Miocene and Pliocene units

Then a series of overlying Miocene units are observed on top of the Eocene/Paleocene units, having been separated by an angular unconformity, where the Eocene/Paleocene units have undergone a series of folding regimes, while the Miocene units tend to be largely planar, with a very low angle of dip, deposited 23 million to 5.3 million years ago. Directly overlying the Dimrill Dale chalk is the Gondor conglomerate, signifying a change in energy from low to high from the Eocene to the Miocene, likely returning to that high energy, wave-dominated environment. The Gondor conglomerate is then overlain by the Rohan tuff, showing the instantaneous deposition of tuff as the result of a nearby volcanic event. The deposits are quite prevalent on the western portion of the quadrangle, with a small deposit in the northeast, showing that the tuff likely came from an eruption further westward, beyond the quadrangle.

The final deposit and youngest unit is the Helm’s Deep sandstone, deposited between 5.3 million and 3 million years ago in the Pliocene. An unconformity separates the Rohan tuff from the Helm’s Deep sandstone, which is an angular conformity in the northwestern fault block, and likely a disconformity in other areas where it overlies the Rohan tuff. The sandstone signifies a slight drop in energy in the depositional environment from the Miocene into the Pliocene, with the possible rising of sea level or uplift.

3. Folds

3.1 Folds in Bree Creek

The Bree Creek Quadrangle is an area that has been subject to a series of several different folding events, evident in both the surface geology, and the subsurface geology and structures. A series of folded Paleocene and Eocene units can be observed in most of the area, with an overturned portion of this series within the central fault block. In the southeastern fault block, a different story unfolds, with original folding of the metamorphic units in one direction, then in the opposite direction, a second phase of folding occurs, causing those folds to become overturned and refolded again. For a reference map of the western, central, and northeastern fault blocks, refer to Fig. 3.1.

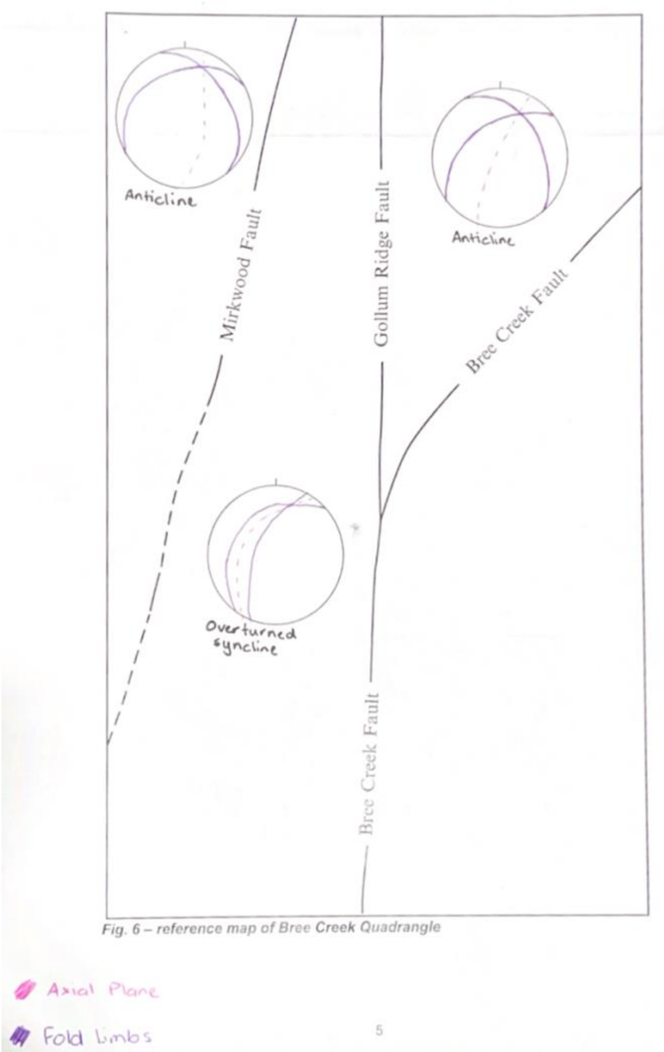


Fig. 3.1. A reference map for the folding of sedimentary units in the western, central, and northeastern fault blocks. Anticlines are observed in the western and northeastern fault blocks, with an overturned syncline in the central fault block separating the two anticlines. The diagrams displayed are based on stereogram analyses of the folding in those three fault blocks, with the two anticlines having a much larger interlimb angle than the overturned syncline in the central fault block, and stand in upright position, while the syncline has been subject to movement, causing the overturning of the fold.

3.2 Western fault block

In the western fault block, stereogram analysis shows a cylindrical anticline that is gently plunging in the northward direction. The fold stands upright, with a gentle interlimb angle of 143°, with straight fold limbs. The axial plane/fold axis has a strike and dip that is measured at 191/85E (refer to Fig. 3.2 for a stereogram analysis of the folding in the western fault block).

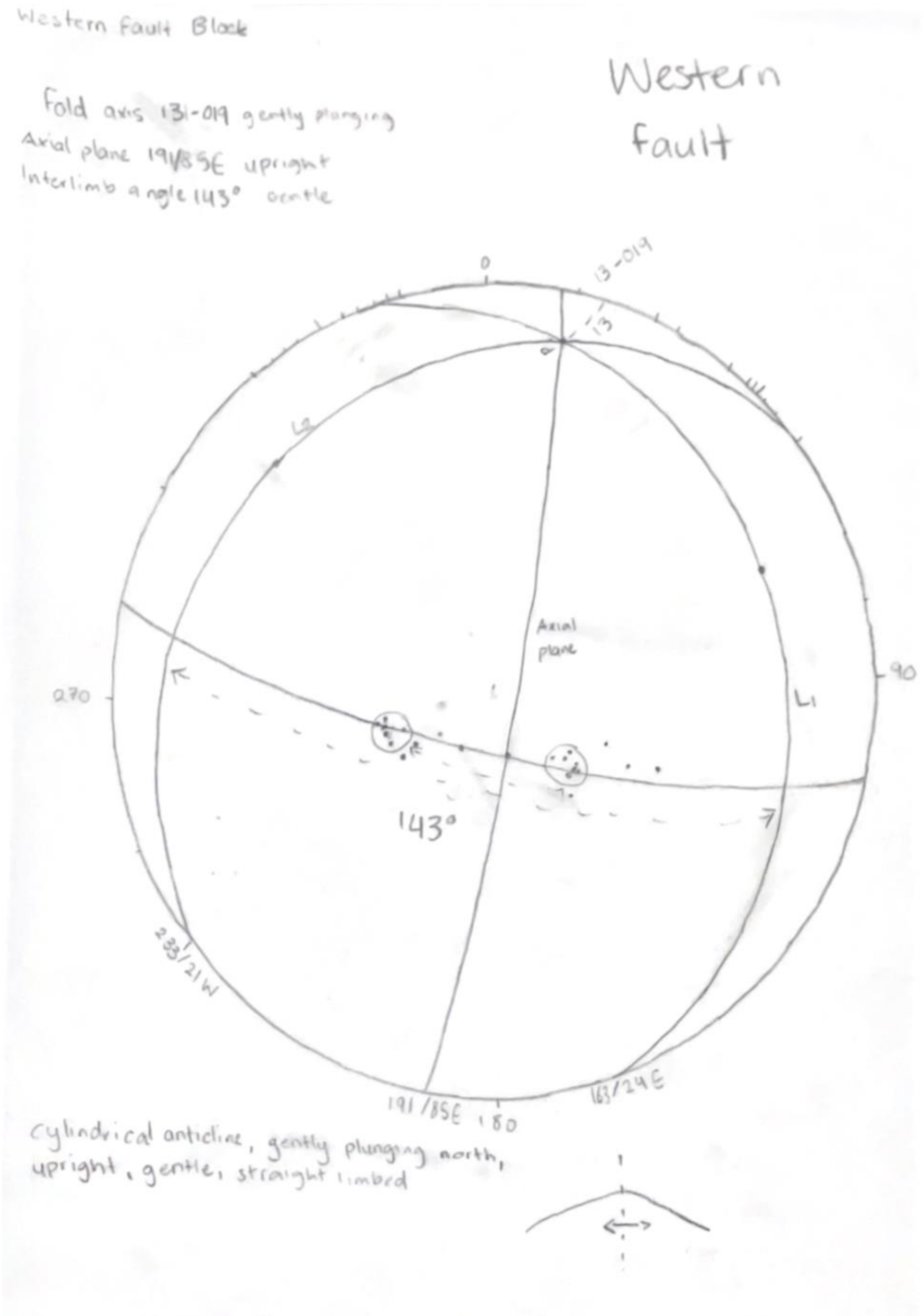


Fig. 3.2 A stereogram analysis of the folds in the western fault block using the poles of the strike and dips in the area. The attitudes and angles of different structures in the stereogram were used for describing the fold.

3.3 Central fault block

In the central fault block, stereogram analysis has shown a cylindrical overturned syncline, that is gently plunging in the northward direction. The attitude of the axial plane shows that the fold is moderately inclined in the westward direction, with an isoclinal interlimb angle of 24°, with straight fold limbs. The strike and dip measured for the fold axis/axial plane sits at 194/53W (refer to Fig. 3.3 for stereogram analysis).

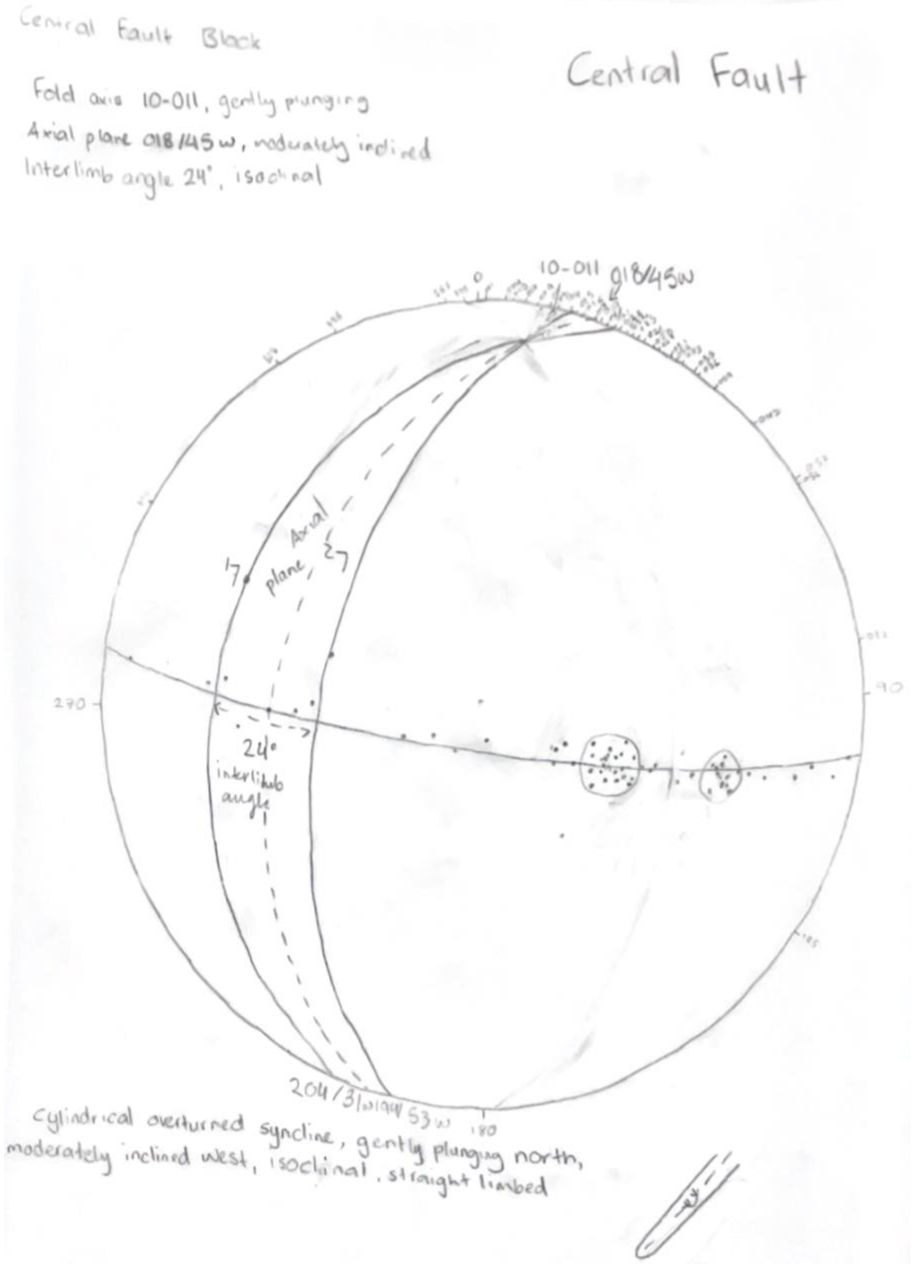
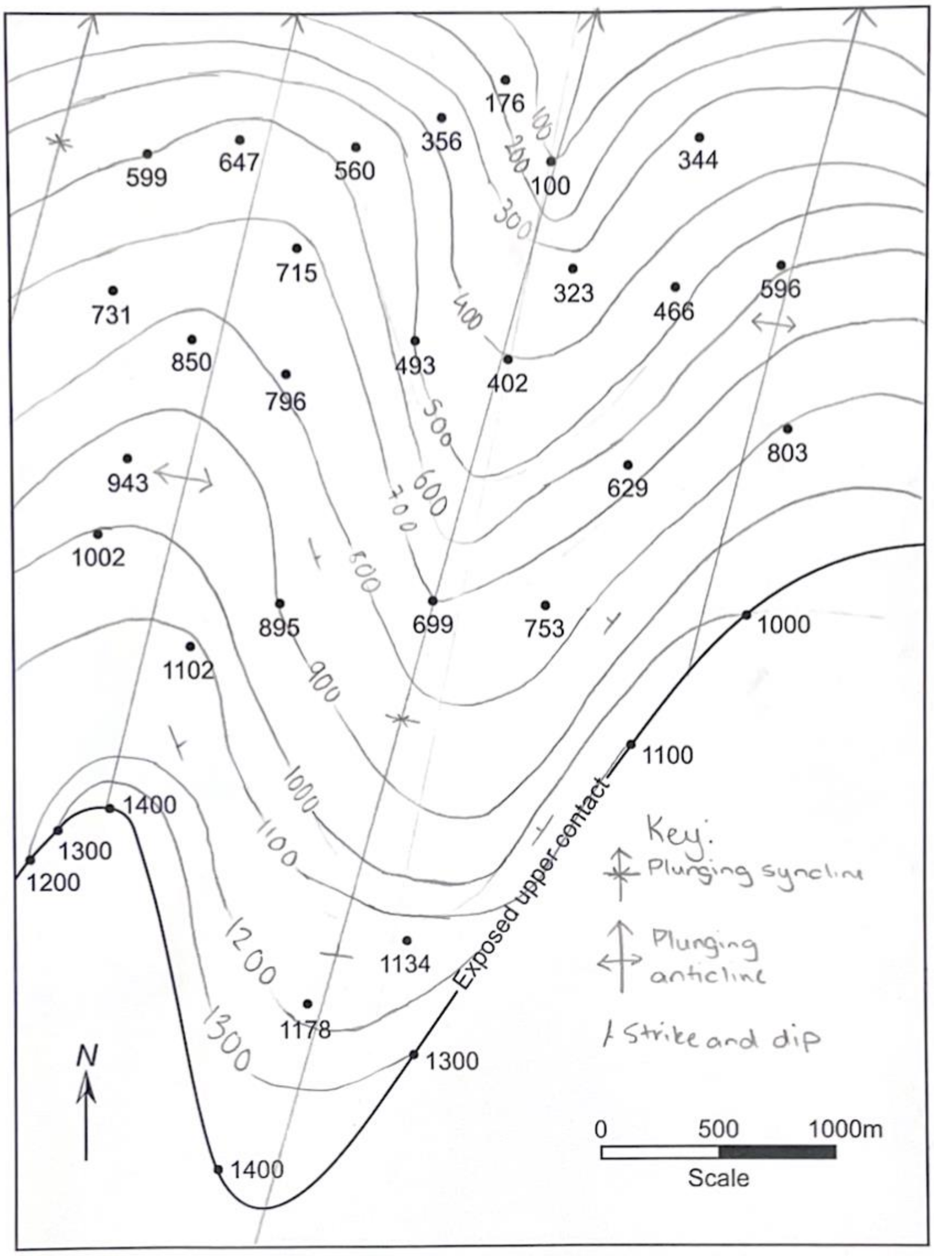


Fig. 3.3 A stereogram analysis of the folds in the central fault block using the poles of the strike and dips in the area. The attitudes and angles of different structures in the stereogram were used for describing the fold.

3.4 Northeastern fault block

In the northeastern fault block, stereogram analysis has shown a cylindrical anticline, that is gently plunging in the northward direction. The fold stands upright, with an open interlimb angle of 109°, with straight fold limbs. The fold axis/axial plane has a strike and dip that is measured at 197/88W (refer to Fig. 3.4. for a stereogram analysis of folding in the northeastern fault block). A series of drill-hole intercepts (refer to Fig. 3.5. for reference map) were taken in the northeastern fault block of the upper surface of the Bree Conglomerate, showing a series of anticlines synclines in the subsurface geology, with a northward plunge, and a northward dip direction of the units with the construction of a 3-dimensional block diagram of the area.

Fig. 3.4. A stereogram analysis of the folds in the northeast fault block using the poles of the strike and dips in the area. The attitudes and angles of different structures in the stereogram were used for describing the fold



Drill-hole intercepts of upper surface of the Bree Conglomerate (meters above sea level)

Block Diagram of NE fault block:

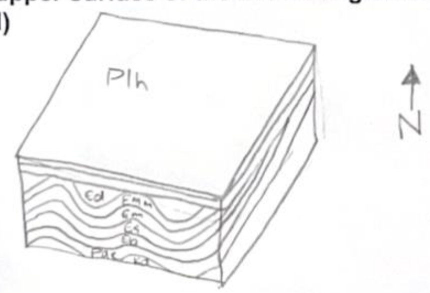


Fig. 3.5.Drill-hole intercepts of the upper surface of the Bree Conglomerate in the northeastern fault block, showing a series of anticlines and synclines plunging in the northward direction. A 3-dimensional block diagram has been constructed to the show the bedding attitudes of the units in the northeastern fault block, where in the subsurface plane, they dip in the northern direction.

3.5 Southeastern fault block

The southeastern fault block is comprised of units that differ from the rest of the units observed in the Bree Creek quadrangle, and underwent two different phases of folding unrelated to the rest of the quadrangle (refer to Fig. 3.6. for a reference map of the southeastern portion, showing fold axes and folding directions).

The first phase of folding was in the vertical direction north-south direction, and trending in the east-west direction (refer to Fig. 3.6.), leading to a series of cylindrical overturned synclines and anticlines. They are gently inclined in the southward direction, and tends to be plunging towards the east. They tend to have a smaller interlimb angle, likely tight or isoclinal.

The second phase of folding was in the horizontal east-west direction, and trending in the north-south direction (refer to Fig. 3.6.), leading to a series of cylindrical anticlines and synclines. The folds stand upright, gently plunging towards the south, with a larger interlimb angle, leading to a more open fold. The second phase of folding has a type two interference pattern, with a recumbent first phase of folding, which has then led to upright folding in the second phase, causing the mushroom shapes observed in Od, and boomerang shapes in Dl (refer to Fig. 3.6.).

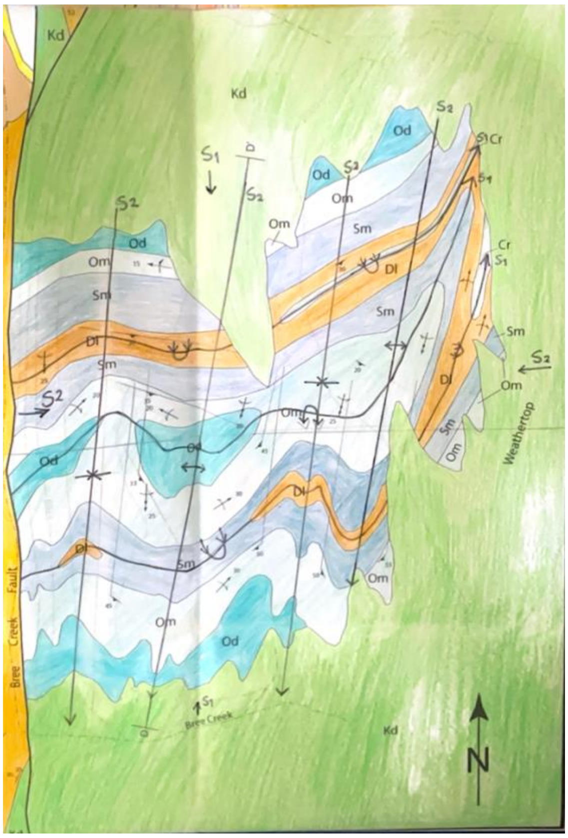


Fig. 3.6. A reference map of the southeastern fault block, showing the two different phases of folding directions and the axial traces in relation to each phase of folding. The first phase of folding consists of a series of overturned synclines and anticlines, while the second phase of folding is represented with a series of upright anticlines and synclines.

4. Faults

4.1 Faults dividing Bree Creek

In the Bree Creek Quadrangle, a series of four faults separate the different portions of the area; from west to east of the quadrangle (refer to Fig. 8.1.), Mirkwood fault, Gollum Ridge fault, Bree Creek fault, and North Bree Creek fault. The faults within the area have caused the uplift, or down throw of different fault blocks and geological units, and possibly being responsible for the burial and metamorphism of certain units and materials. With the use of cross-sections and the geologic map of the area, the attitude, type, age, and the strike separation and dip separation were able to be calculated and applied to make a full description of each fault.

4.2 Mirkwood fault

The Mirkwood fault lies on the western most side of the quadrangle, separating the western fault block from the central fault block. Mirkwood fault is an oblique right-lateral reverse fault, that tends to have varying strike depending on where in the map the strike is being measured, but sits roughly at 013, with a dip of 45W. Based off analysis of A-A’ cross section (refer to Fig. 8.2.), a strike separation of 200m was measured, with a dip separation of 1800m. The exact age of the fault is unknown, but based off the youngest unit that it cuts and the overlying unit, it can be inferred that the age of the Mirkwood fault sits between the post-Miocene and pre-Pliocene.

4.3 Gollum Ridge fault

The Gollum Ridge fault lies in the centre of the quadrangle, separating the western fault block, and northeastern and southeastern fault blocks from the central fault block. The Gollum Ridge fault is an oblique left-lateral normal fault, with an attitude of 173/75W, but the strike of the fault tends to vary very slightly from north to south. With the use of the A-A’ cross section (refer to Fig. 8.2.), a strike separation of 1400m, and a dip separation of 900m was measured. The exact age of the Gollum Ridge fault is uncertain, but the youngest unit the fault cuts through is Miocene in age, so with the use of relative dating, a post-Miocene age can be inferred for the fault.

4.4 North Bree Creek fault

The North Bree Creek fault sits on the northeastern end of the quadrangle, separating the northeastern fault block from the southeastern fault block, and connects with both the Gollum Ridge fault and the Bree Creek fault. The North Bree Creek fault and the Bree Creek fault are the same fault, but the two faults have varying attitudes, hence the separation of the two portions of the fault. The North Bree Creek fault is an oblique left-lateral normal fault, with an attitude of 029/80NW on the most western portion of the fault, but strike tends to increase the more eastward the fault moves. The strike separation and dip separation are indeterminate, because the units seen in the northeastern fault block and the southeastern fault block are not the same, or it is these units that have been metamorphosed in the southeastern fault block, meaning a strike and dip separation cannot be measured. However, a post-Miocene age for the fault can be inferred based on the youngest unit that the fault cuts through.

4.5 Bree Creek fault

The Bree Creek fault connects with the Gollum Ridge fault and the North Bree Creek fault, making up the southern central portion of the map, separating the southeastern fault block from the central fault block. The Bree Creek fault is an oblique left-lateral normal fault, with a strike that may vary geographically depending on what portion of the fault is being observed, but sits approximately at 005/80NW. Again, the strike separation and dip separation of the fault is indeterminate, for the same reasons those measurements are indeterminate for the North Bree Creek fault. A post-Miocene age can be inferred for the Bree Creek fault, due to the youngest unit being cut by the fault being Miocene in age.

5. Orientation of principal stresses

5.1 Principal stresses

When a rock has forces acting on it, it is under stress from all different directions whereby three principal planes of stress that all have normal stresses acting upon it, known as principal stresses. $\sigma1$ is the greatest principal stress, $\sigma2$ is the intermediate principal stress, and $\sigma3$ is the least principal stress, and they all act orthogonal to one another. Where $\sigma1$ is acting vertically and $\sigma3$ is acting horizontally, there were extensional regimes where normal faulting will occur, and where $\sigma3$ is acting vertically and $\sigma1$ is acting horizontally, we have compressional regimes, leading to reverse faulting. By analysing the principal stresses acting on different units to form different rock types, a history of the area can be reconstructed for the Bree Creek Quadrangle, allowing us to understand the different tectonic regimes that influenced the structures seen today in the region.

5.2 Folding of Paleozoic units

The Paleozoic metamorphic units within the southeastern fault block have been subject to two different phases of folding, whereby the first phase shows a series of overturned anticlines and synclines, and the second phase shows a series of upright anticlines and synclines. For folding to occur, compressional regimes would have had to be in place, meaning $\sigma1$ would have been acting horizontally and $\sigma3$ acting vertically. In the first folding phase $\sigma1$ must have been acting horizontally with $\sigma3$ acting vertically to have a compressional regime for folds to occur in. There is a bit of uncertainty associated with the overturning of the units, whether it was caused by faulting or another tectonic regime, and because they are metamorphic, it is hard to tell whether the folding occurred before or after metamorphism. As for the second phase of folding, the same compressional regime would have been acting on it, but it is uncertain whether this is the same regime as the Paleocene and Eocene units, or earlier or later.

5.3 Folding of Paleocene and Eocene units

For the Paleocene and Eocene sedimentary units, for folding to occur, a compressional regime must be in place, whereby $\sigma1$ would need to be acting horizontally, and $\sigma3$ would need to be acting vertically.

5.4 Mirkwood fault and overturning of the central fault block

At the same time at which the folding of the Paleocene and Eocene units was occurring, the same set of principal stresses would have been in place, where $\sigma1$ is acting horizontally and $\sigma3$ is acting vertically, for Mirkwood fault to appear as a reverse fault. In a reverse fault the hanging wall side moves up, with the footwall side moving down relative to the other wall. The central fault block sits in the hanging wall side of the Mirkwood fault, which has allowed for the upward movement of the central fault block, which meant that as $\sigma1$ kept acting horizontally, it pushed the fault block upwards, causing the syncline to become overturned.

5.5 Gollum Ridge fault and Bree Creek fault

Both the Gollum Ridge and Bree Creek faults are observed as normal faults (refer to Fig. 8.3. and 8.4.), which would mean extensional regimes would have had to have been in place. At this time, $\sigma1$ would have been acting vertically, with $\sigma3$ acting horizontally, causing the footwall side to move up relative to hanging wall side. In the cross sections A-A', B-B', and C-C' (Fig. 8.2., 8.3., and 8.4.), the units on the footwall side have moved up, relative to the footwall side of the faults. The two faults may have occurred simultaneously, they both have an inferred post-Miocene age, meaning that it's likely they were both formed under the same extensional regime.

6. Discussion

6.1 Relationship of faulting, folding, and stratigraphy

The different tectonic regimes and stresses acting on the units have been responsible for the faulting and folding of different units, which has led to a complicated stratigraphy for the Bree Creek Quadrangle.

It is likely that the folding of the Paleocene/Eocene units, and possibly the Paleozoic units (?), occurred within the same compressional regime as the Mirkwood fault, with the same principal stresses acting upon it. The Mirkwood fault likely moved more than once, as the fault cuts through the mostly planar Miocene units, suggesting the folding and first slip of the fault happened simultaneously, then the deposition of the Miocene units was deposited and the second slip might have cut through those later on, post-Miocene. Recalling from previously, the overturning of the syncline in the central fault block is likely the result of the upward movement of the footwall in that compressional regime, causing that portion of the central fault block to move upwards, and overturning the syncline, which can be visually observed in the cross sections A-A' and B-B', where sense of movement lines up with the overturning of the unit. As for the Gollum Ridge and Bree Creek faults, the folding preceded the occurrence of these two faults, as they have formed under an extensional regime, showing a shift towards an extensional regime in the post-Miocene age. Gollum Ridge appears to have only slipped once, with not a large geographic extent, and is relatively even with very little variations in terms of its attitude. However, the Bree Creek fault likely slipped twice, changing its direction of movement from an east-west displacement to a south-north displacement, or vice versa. It is hard to tell in which orientation it started and eventually moved to because the units observed in each fault block differ, causing a lot of uncertainty in analysis (refer to map to observe different units).

6.2 Structural events

Sedimentation, erosion, intrusion and metamorphism may be related to structural events. In terms of sedimentation and erosional regimes in relation to structural events, faulting and uplift of material means that material that was once at depth is now exposed, leading it susceptible to a series of erosional regimes (e.g. precipitation, fluvial and wave processes), meaning the eventual lowering of uplifted units. When material is eroded, it can be transported elsewhere, where it can deposit, and over time enough will be deposited to make up an entire new unit in a different geographic location, showing the extent of sedimentation in relation to faulting. This may be the case for the distribution the Rohan Tuff, where material from nearby volcanism has been eroded and transported a distance, and later deposited in the areas where it can be seen on the map (refer to map).

It is possible the intrusion of the Dark Tower granodiorite was responsible for faulting events, and may be the source for where fluid from depth has travelled through to be released at the surface. Metamorphism of the southeastern fault block may have also been a result of faulting, whereby a high amount of pressure and temperature may cause metamorphism to occur, possibly in the first slip of the Bree Creek fault. As for the stress orientation, it started off in a compressional regime, where $\sigma 1$ was acting horizontally and $\sigma 3$ acting vertically, likely during the Paleozoic through to the Mesozoic to form the folded units and the Mirkwood fault. However, post-Miocene into the Pliocene, a change in the stress orientation changed, whereby $\sigma 1$ was now acting vertically with σ3 acting horizontally, leading to an extensional regime, leading to the occurrence and ruptures of the Gollum Ridge and Bree Creek normal faults. Based off stereonet analysis (refer to Fig. 6.1.), it is known that the Rohan tuff had a slightly lower dip in both the central fault block and the northeastern fault block. In the central fault block, the Rohan tuff had an attitude of 260/01 NE, and then post-tilting of the Helms Deep sandstone, the attitude stood at 158/07 NE, meaning a higher degree of tilting took place post-Miocene. The same story unfolds for the northeastern fault block, where the original attitude of the Rohan tuff stood at 198/07 SE, and post-Miocene tilting allowed for a change in dip direction of 164/09NE.

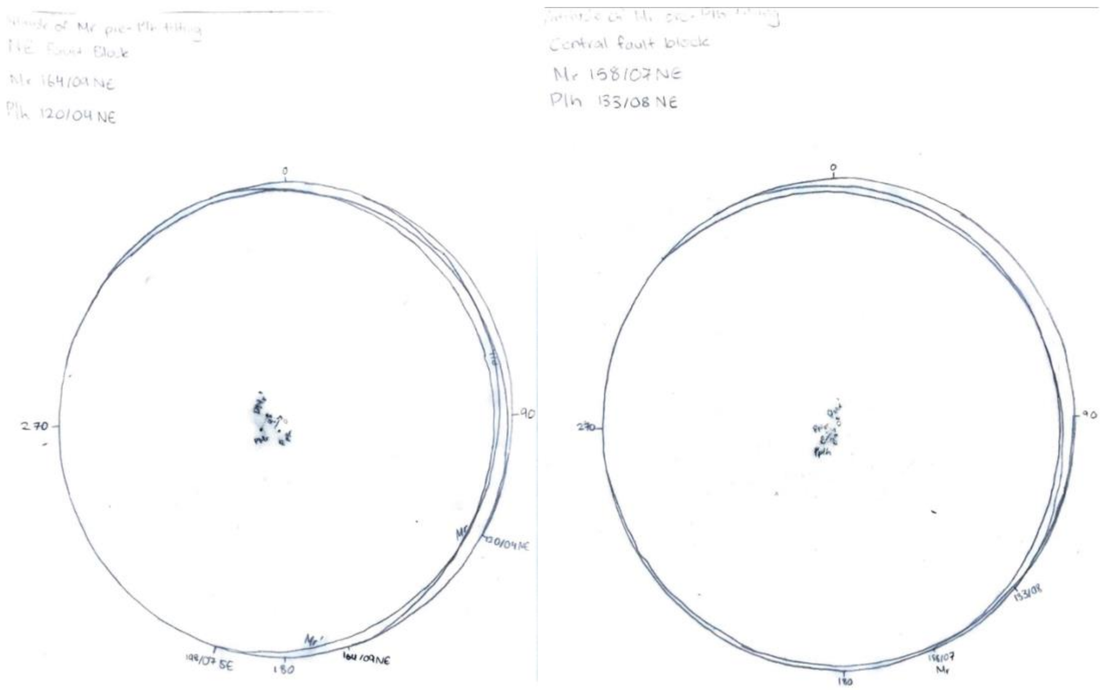


Fig. 6.1. Stereonet analyses of the attitude of the Rohan tuff before the tilting of the Helm's Deep sandstone in the northeastern fault block (left image) and central fault block (right image). Post-Pliocene when the Helm's Deep sandstone was deposited, tilting occurred again, causing the two fault blocks to increase in their angle of dip, making them slightly less planar than their original deposition. This method was done by plotting the poles of the sandstone and the tuff, then moving the sandstone to the centre to make it vertical, and moving the sandstone the same degree in the same direction, allowing an attitude pre-tilting of the sandstone to be measured.

7. Geologic/structural history

The geologic/structural history of the Bree Creek Quadrangle is a complex one, with changes in stress orientation, folding, faulting, volcanism, and changes in the depositional environments.

7.1 Paleozoic and Mesozoic deposition

Starting with the oldest units, the deposition of the Paleozoic metamorphic protoliths, the first being the Mt. Doom schist, then the Minas Tirith quartzite in the Ordovician, followed by the Moria slate in the Silurian. Then the Lonely Mountain quartzite in the Devonian and then the Rivendell marble in the Carboniferous, which is when the first phase of folding likely happened. An igneous pluton in the Cretaceous, the Dark Tower granodiorite, then intrudes through these Paleozoic units, but it is unsure whether the metamorphism had occurred at this stage. It is possible the pluton induced metamorphism, but faulting later in the history of the area may also be responsible for the metamorphism. Depositional environments are hard to infer as the contents of the protoliths are unknown, but burial with the influence of heat and temperature had to have occurred for metamorphism to take place.

7.2 Paleocene and Eocene deposition

Then in the Paleocene the deposition of the Edoras Formation occurred, leaving a nonconformity between the Edoras Formation and the Paleozoic metamorphic units, and the Mesozoic igneous pluton. Afterwards during the Eocene, a series of sedimentary units were deposited, starting with the Bree conglomerate, then The Shire sandstone, Mirkwood shale, Misty Mountain limestone, and finally the Dimrill Dale chalk. Then the folding of those units occurred under a compressional regime where a possible first slip of the Mirkwood fault occurred. It is possible that under this same compressional regime that the second phase of folding for the metamorphic units occurred, but this is not entirely certain. As the Mirkwood fault ruptured, it is likely that this influenced the overturning of the Paleocene/Eocene units in the central fault block occurred.

7.3 Miocene and Pliocene deposition

The deposition of the Gondor conglomerate then occurred with the transition into the Miocene from the Eocene, where it sits on top of an angular unconformity. Then later in the Miocene, volcanism led to the deposition of the Rohan tuff, where not long after, a very small amount of tilting for the Miocene units occurred. At this stage, a possible second slip of the Mirkwood fault occurred to cut through the Miocene units in the northern region of the quadrangle. It is possible that at this stage in the late Miocene, the rupture of the Gollum Ridge and Bree Creek faults occurred, although this could also be post-Pliocene, but this information is uncertain as the two faults aren't in contact with any of the Pliocene unit. The faults brought up the Paleozoic metamorphic material from depth, and possible the Mesozoic intrusion as well, with possible deposits of younger sedimentary units being eroded away because of uplift. It is likely the most recent event of the Bree Creek Quadrangle was the deposition of the Helm’s Deep sandstone in the Pliocene.

8. Figures

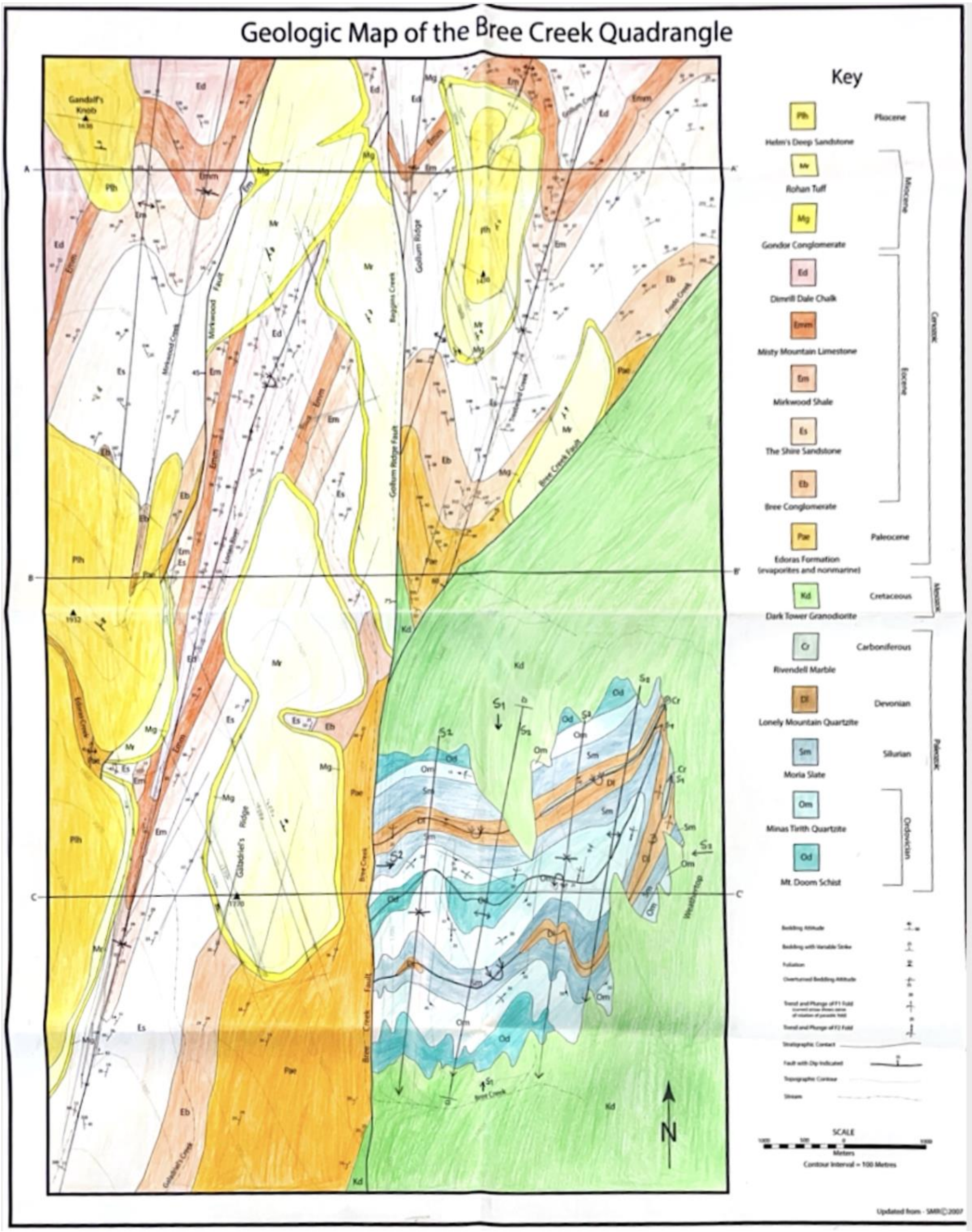


Fig. 8.1. Geologic map of the Bree Creek Quadrangle, where the different symbols represent different types of geologic structures on the surface of the quadrangle, and the colours represent the different units, with a full key of the ages and colours associated with each unit. For subsurface details, refer to the cross sections in Figs. 8.2., 8.3., 8.4., and 8.5. The distribution and extent of units and geologic structures can be followed with the scale, and with the cross section figures.

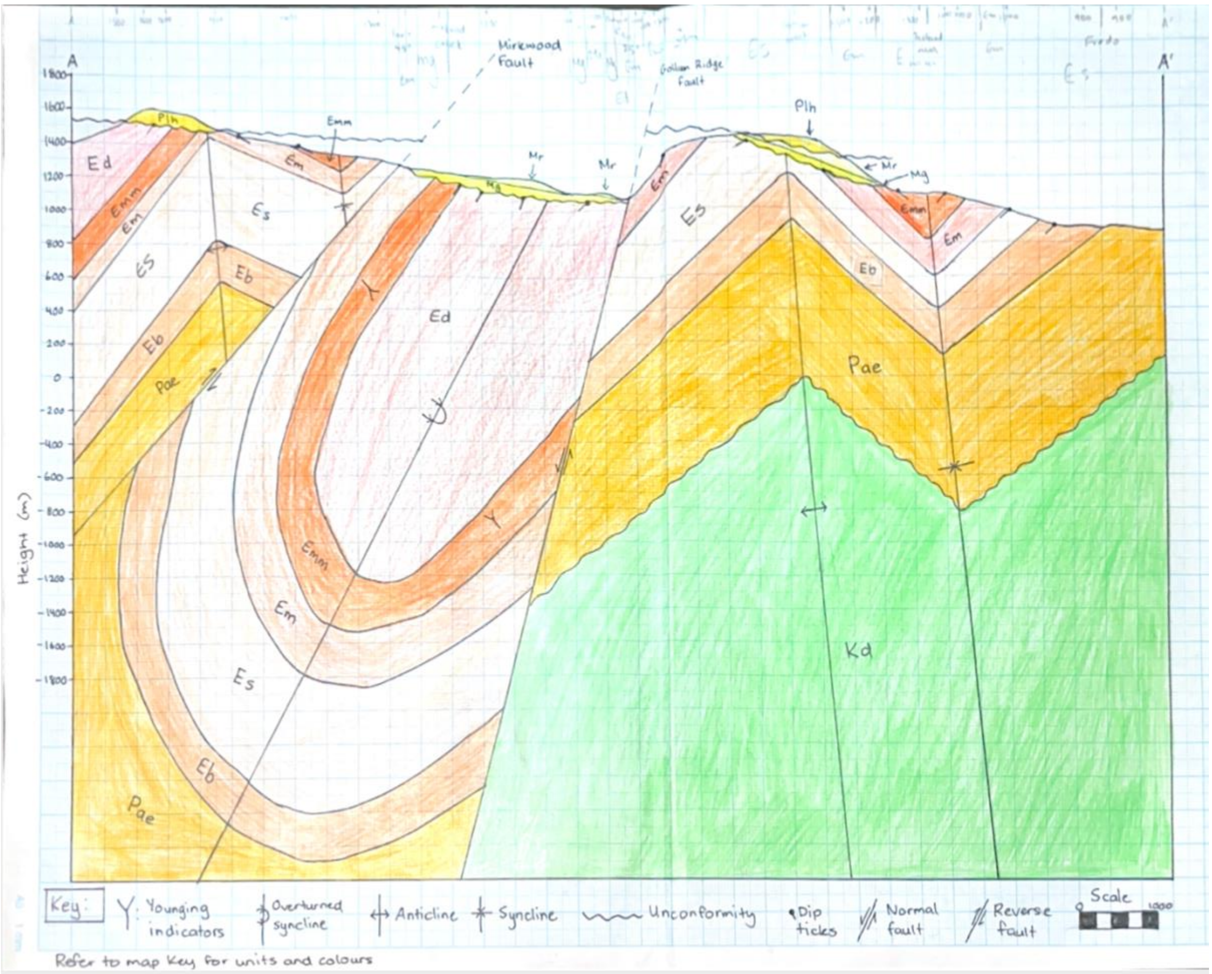


Fig. 8.2. A cross section of the A-A' line (refer to Fig. 8.1. for cross section line). In this cross section the sedimentary units and igneous pluton make up the distribution, with the Mirkwood fault and Gollum Ride fault cutting through the units in this particular section. The overturning of the central fault block can be understood with the sense of movement of the Mirkwood fault. The units folded are Paleocene and Eocene in age, with the slightly tilted Miocene and Pliocene units that overlie those. Because of the shear of the Gollum Ridge fault, the Cretaceous igneous intrusion is insight in the section, due to the uplift of the footwall.

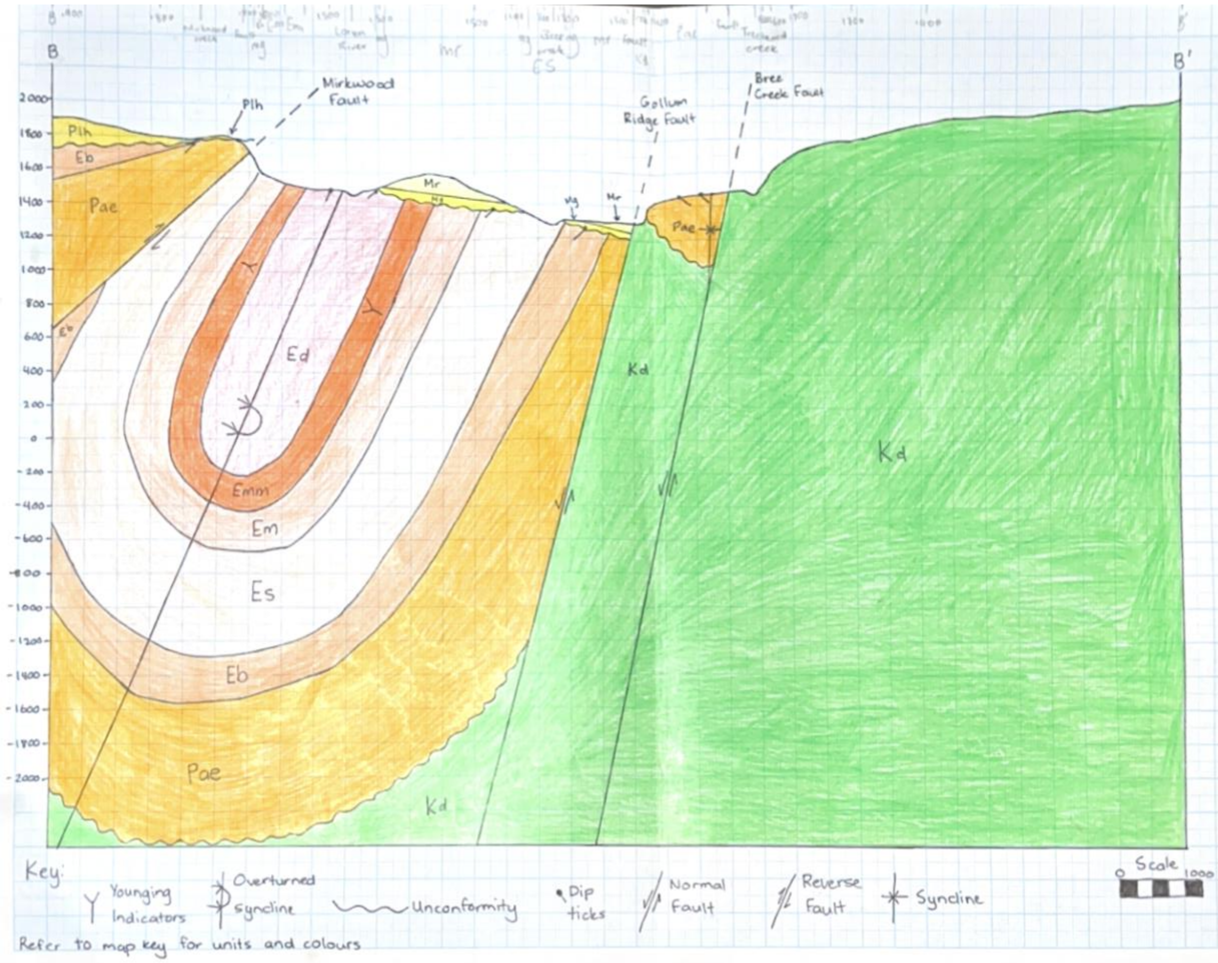


Fig. 8.3. A cross section of the B-B' line (refer to Fig. 8.1. for cross section line). In this section all three faults intersect the line, displaying the sense of shear of each fault perfectly. Upward shear of the Bree Creek fault has caused the large extent of the Dark Tower granodiorite, alongside with the downward shear of the hanging wall, allowing the Edoras formation to be lowered slightly into the sub-surface. The overturning of the central fault block can again be understood with the sense of shear from surrounding faults.

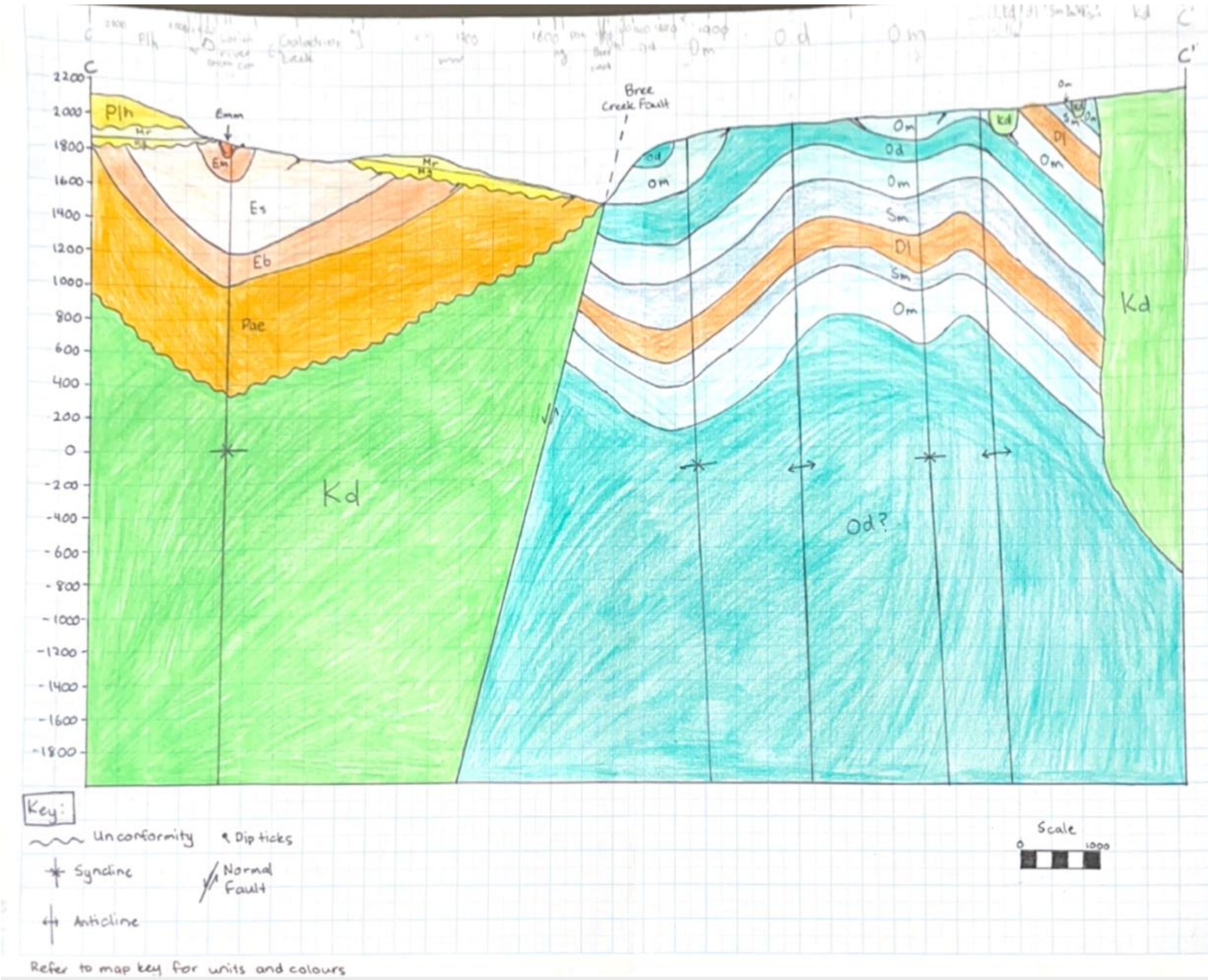


Fig. 8.4. A cross section of the C-C' line (refer to Fig. 8.1. for cross section line). In this section, the syncline in the central fault block does not appear to be overturned here, due to erosional effects, causing the beds on each limb to dip towards the core. The upward shear of the Bree Creek fault has allowed for the buried metamorphic material to be brought up closer towards the surface, with some beds being exposed. In the southeastern fault block, beds of the same unit appear to overlap, due to a second phase of folding, which led to the overturning of the first phase folds. The depths and thicknesses of the metamorphic units have been taken from where it intersects with the D-D' section (Fig. 8.5.), but the Od at the bottom is only interpretive because no subsurface samples have been taken of this region.

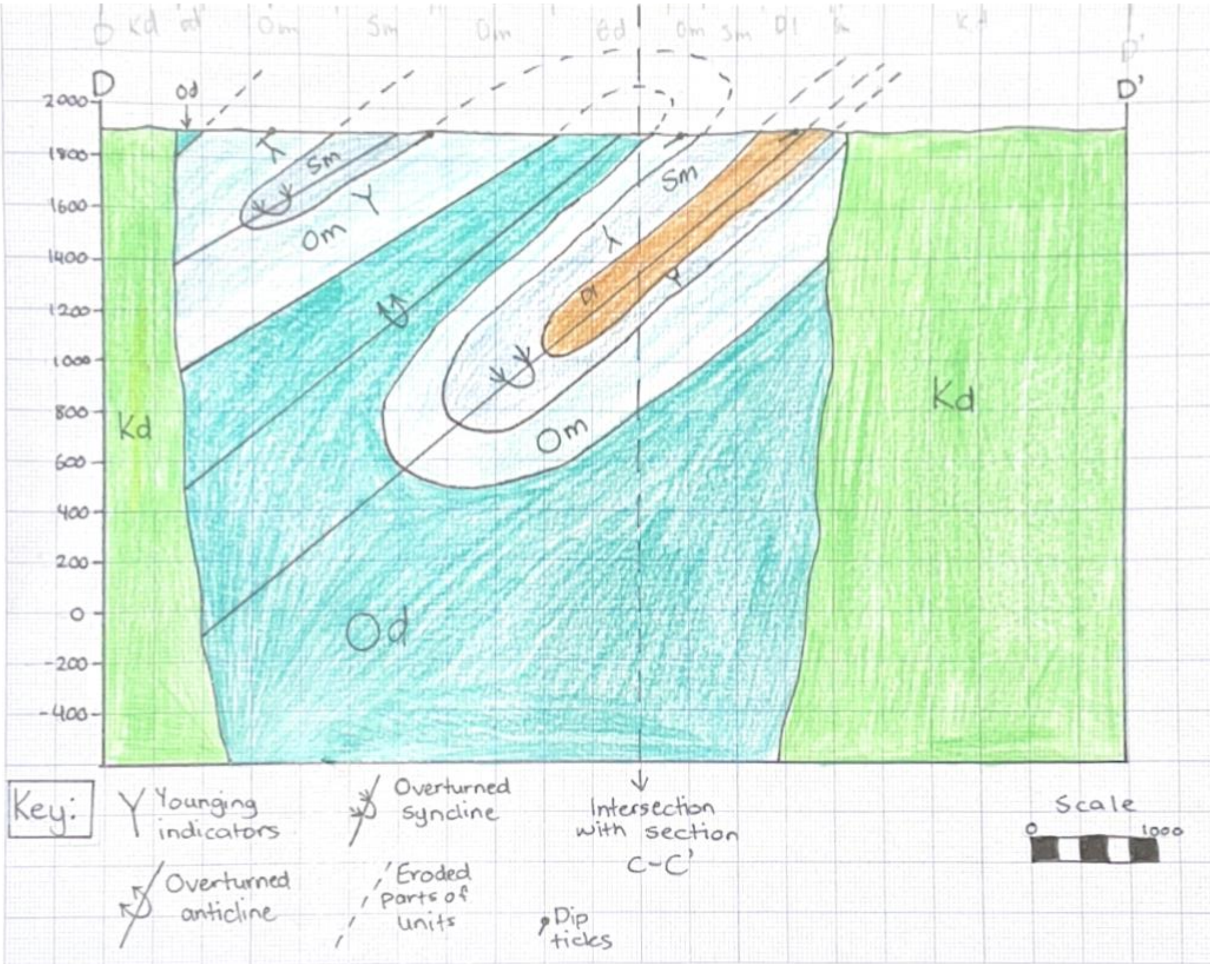


Fig. 8.5. A cross section of the D-D' line (refer to Fig. 8.1. for cross section line). This section only analyses the metamorphic units in relation to the igneous pluton. The extent of Kd is only interpretive, without sub-surface samples it is impossible to tell the full extent and attitude of the unit. The same goes for Od, which is interpreted only because it is the oldest of the metamorphic units, but this could very well be Kd intruding through that section. The overturning and second phase folding has meant that the units appear to thin and thicken throughout the section. The intersection with the C-C' section are the thicknesses used for the thicknesses of the metamorphic units for the C-C' section.