A REVIEW OF ROCK WEATHERING IN ANTARCTICA

AND ITS RELATIONSHIP TO STUDIES IN THE NORTHERN HEMISPHERE

Abstract: Some of the literature on rock weathering in the Northern Hemisphere and in Antarctica was reviewed. Particular emphasis was placed on the processes involved, especially freeze-thaw, and their relationships to climate and the properties of the rock. The interaction between the studies conducted in the Northern Hemisphere and in Antarctica was explored and any potential lessons that the latter might have to the overall debate on rock weathering in cold climates highlighted. The results indicate that studies on rock weathering in Antarctica have a significant contribution to make to this debate but that Northern Hemisphere research takes little cognisance of this.

Christine Elliott

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1. INTRODUCTION

Weathering is defined by Yatsu (1988, p2, citing Correns, 1939) as "the alteration of rock minerals *in situ*, at or near the surface of the earth and under the conditions which prevail there". The use of the tenn *in situ* distinguishes weathering from erosion, which involves the transport of material. Goudie (1994 p556) believed weathering to be "one of the most important of geomorphological and pedological processes ....".

The processes of weathering are often classified into mechanical (physical), chemical or biotic (biological) (Selby, 1993), and it is generally accepted that mechanical weathering is the predominant one in cold climate environments (e.g. Campbell & Claridge, 1987; Matsuoka, 1995), although some chemical (e.g. Ishimaru & Yoshikawa, 2000) and biological (e.g. Hirsch, et al., 1995) weathering does occur. Consequently French (1996), preferred the term cryogenic weathering meaning the combination of mechanico-chemical processes, which cause the *in situ* breakdown of rock under cold climate conditions.

According to Selby (1993) the most significant factors affecting the rate of weathering are climate and the physical and chemical composition of the parent rock and the most commonly recognised physical weathering processes are:

- Internal rock stress
- Insolation
- Frost action
- Salt crystal growth
- Wetting and drying

Site factors are also important, especially the rate of soil drainage. However, rock break-up will only occur when the forces exerted are greater than the strength of the rock (Hall, 1987).

Although there is a wealth of knowledge from Antarctica, most studies on rock weathering in cold climates have been undertaken in the Northern Hemisphere and have focussed on freeze-thaw in particular (Hall, 1992). Matsuoka (1995) pointed out however, that whilst frost weathering was considered dominant in humid cold regions, little was known about its efficacy in cold deserts. Consequently the purpose of this paper is to review some of the literature on rock weathering in both the Northern Hemispbere and the Antarctic, with a particular emphasis on the processes involved and their relationship to climate and rock properties. The role of freeze-thaw is especially highligh1ed. The key results from the Antarctic studies will be identified and any contribution that the studies in Antarctica might have to the overall debate on rock weathering in cold climates highlighted.

2. DEVELOPMENTS IN THE NORTHERN HEMISPHERE

2.1. FREEZE-THAW

Initial theory on the freeze-thaw mechanism was based on the assumption that weathering was a result of the 9% expansion of water in either cracks (frost action) or between grains of rock (frost weathering) as it froze and subsequently thawed. Early experiments concluded that it was the frequency of these freeze-thaw cycles (i.e. crossings of the 0°C air temperature) that caused the rock to break down (e.g. Russell, 1943). However, subsequent studies showed that these cycles could be few or even absent in cold climate environments (Fahey, 1973) and the results of other research into intensity,. rate (e.g. Lautridou & Ozouf, 1982) or type of cycle (e.g. Wiman, 1963) were inconclusive and/or contradictory. Some also noted that very small amounts of debris were actually produced during these experiments (Wiman, 1963; Potts, 1970; Brockie, 1972).

Susequently McGreevy (1981) recognised that more than one rock weathering mechanism could operate and that the nature of the rock, moisture supply and thermal conditions also needed to be considered. McGreevy and Whalley (1982) also found that air temperatures were poor indicators of rock temperatures and that laboratory experiments on small samples of 'intact' rock need not necessarily reflect what happened in the field with 'massive' rock. Fahey and Lefebure (1988), in a field experiment, identified that there were fewer freeze-thaw cycles in rock than in air and that these reduced with depth. In addition, maximum debris release closely corresponded with maximum groundwater seepage and access to moisture was found to be an important factor in other studies on freeze-thaw (e.g. Matsuoka, 1990a).

Several attempts were made to build theoretical or mathematical models (Hallet, 1983; Walder & Hallet, 1985; Tharp, 1987; Matsuoka, 1990b) and Walder and Hallet (1985) introduced the idea that water might migrate within rock to form segregation ice, as an alternative to the 9% volume expansion theory. Matsuoka (1990a) confirmed that volumetric expansion was not the unique cause of frost shattering and, in his predictive model (Matsuoka, 1990b), that freeze-thaw frequency on the rock surface was a more important parameter than either degree of saturation or the tensile strength of the rock. Finally, there was growing recognition that freeze-thaw might not be the dominant mechanism in some circumstances (Boelhouwers, 1993; Hall, 1995; Halsey et al., 1998) and that interrelationships between processes might operate (Hall, 1992).

2.2. SALT WEATHERING AND FREEZE-THAW

Salt weathering is believed to result from stresses in rock caused by the crystallization of salts in rock pores through either the growth of crystals from solution, thermal expansion or hydration (Selby, 1993; Fahey, 1985; Goudie, 1994), although other mechanisms have also been suggested (Williams & Robinson, 1991). The salts come either from the sea or inland lakes or are derived from the chemical weathering of the rock itself (Selby, 1993) and are widely recorded throughout the Polar Regions (Williams & Robinson, 1981), including Antarctica (Evans, 1970, cited in McGreevy, 1982). However, Selby (1993) noted that magnesium sulphate ($MgS0_4$) and thenardite (Na_2S0_4) might be relatively uncommon in most inland deserts. A number of studies have cited the potential importance of salt weathering in cold environments, including Antarctica (e.g. Rodriquez-Navarra & Doehne, 1999).

Several attempts have been made to measure the combined action of freeze-thaw and salt weathering or to make comparison between them. Williams and Robinson (1981) for example found that the presence of salt enhanced rates of frost weathering whereas McGreevy (1982) found the opposite. Fahey (1983) put this contradiction down to the different levels of salt used in these two experiments. McGreevy (1982) also found that halite (NaCl) had greater effect than either thenardite or $MgS0_4$, whereas most others found that thenardite had greater effect (e.g. Williams & Robinson, 1981; Fahey, 1983). Fahey (1983), who also considered hydration as well as freeze-thaw and salt weathering, found that the presence of salt increased both hydration and frost weathering but that this depended on both the salt and the type of rock. He also noted that the actual amount of salt in solution in rocks was unknown. Finally Goudie (1999) found that resistance to salt was a poor predictor of resistance to frost in limestone.

2.3. HYDRATION AND INSOLATION WEATHERING

Whilst there have been some studies conducted on the hydration process in cold enviromnents (Fahey, 1983; Fahey & Dagesse, 1984; Hall& Hall, 1996) the low moisture in Antarctica means this is not a very important process there. However, Hall and Hall (1996) found that wetting and drying had an effect on the internal characteristics of the rock which could influence the nature and degree of other weathering processes and Fahey (1983) noted that this process operated throughouth the year.

Early studies on thermal expansiOn and contraction found that it was unlikely to weather rocks (Blackwelder, 1933; Griggs, 1936, cited in Selby, 1993), although a repeat of these did find some rnicrofracturing (Aires-Barros et al., 1975, cited in Selby, 1993). Yatsu (1988) however, estimated that heating rates of greater than 2°C per minute could produce cracking and permanent strain in rocks and that the cracks were most likely to occur along grain boundaries. Coutard & Francou (1989) also found that a granite rock surface in the French Alps experienced a 30°C temperature range and that diurnal fluctuation was still perceptible at 48cm within the rock.

2.4. St !VIMAR\'

In summary therefore, the Northern Hemisphere studies found no conclusive evidence that either freeze-thaw or salt weathering acting individually or together were effective mechanisms in rock disintegration nor was there clarity on how the mechanisms worked. Some continued to note that little debris was produced by freeze-thaw (e.g. Lautridou & Seppala, 1986; Tharp, 1987). In addition, with a few notable exceptions (e.g. Lautridou & Seppala, 1986; Fahey & Lefebure, 1988), these studies were primarily undertaken in the laboratory and on sedimentary rock, usually limestones or sandstones. Although the importance of temperature, moisture and rock properties was recognised there was no clear evidence as to which freeze-thaw cycle may be the most effective nor what type or concentration of salt. Little cognisance was taken of insolation weathering.

3. ANTARCTIC STUDIES

According to Campbell and Claridge (1987), whilst physical weathering is the dominant process of rock decay in Antarctica, its low moisture means that water based processes are not very effective there, freeze-thaw is comparatively restricted, and weathering is much less intensive than in the alpine or subalpine zones of more temperate areas. Salt weathering is stated as being the dominant process in the Dry Valleys but there is little evidence to indicate that insolation weathering was a significant mechanism. They also identified six different climatic regions.

Recent studies fall largely into two groups; those that have been conducted in the Maritime Antarctic and those that have been conducted in the more arid cold desert environments. Figure 1 indicates the main locations of these studies.

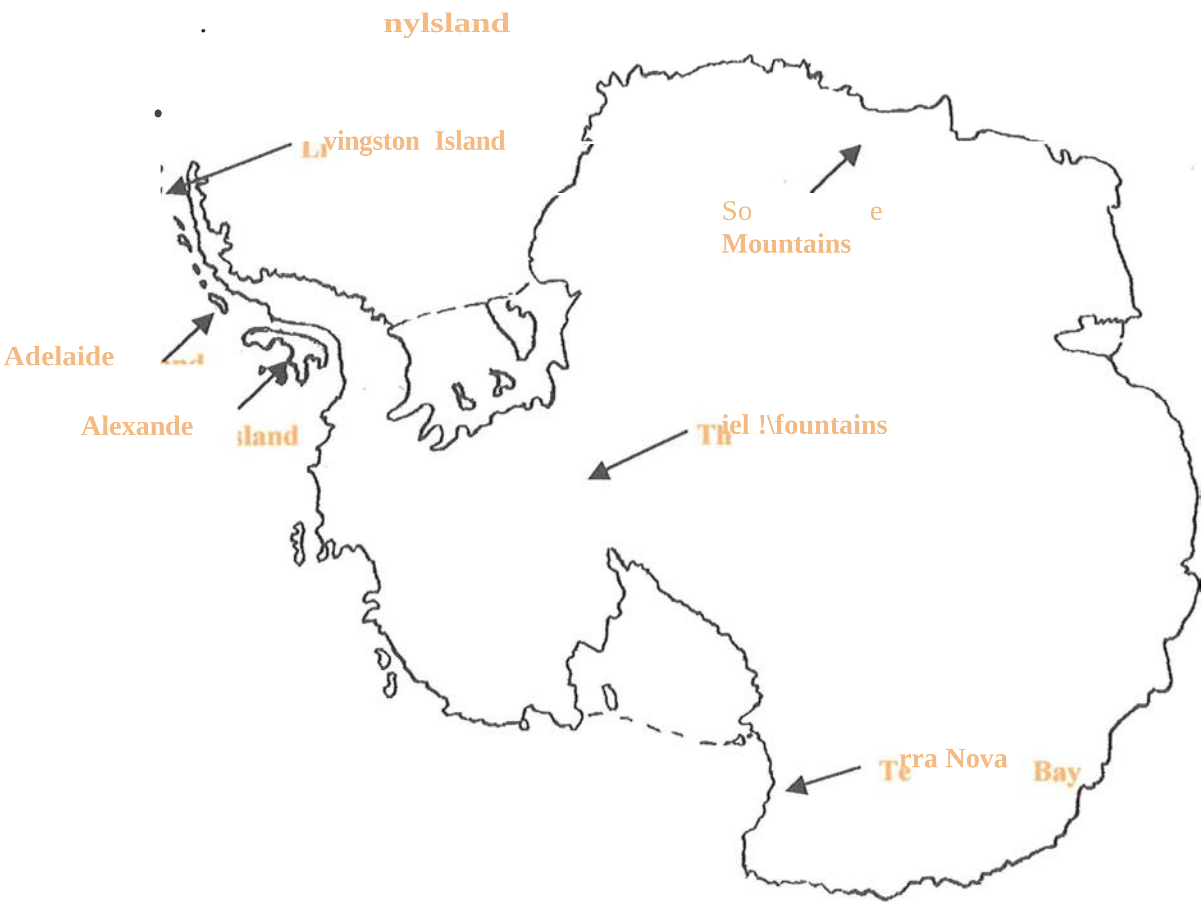

Figure 1. Antarctica, indicating the location of the d(fforent studies discussed in the text.

3.1. MARITIME ANTARCTIC

Campbell and Claridge (1987) identified the Maritime Antarctic as the west coast of the Antarctic Peninsula and the islands north of 55°S. The temperature range is -12°C to +12°C with precipitation between 200 and 1000mm per annum. The soils are moist and ground temperatures may rise above freezing for short periods in any month of the year.

3.1.1. Si 11v Islattd

Signy Island (Figure 1) has a cold oceanic climate with mean monthly temperature of approximately -4°C and low precipitation (400mm per year) and sunshine (on average 1.5 hours per day) (Hall, 1986). Geologically the island consists of metamorphosed sediments, mainly quartz-micaschist (citing Mathews & Maling, 1967).

A number of rock samples from different locations on Signy Island were tested and Hall (1986) found that moisture content was a major factor in rock weathering here but that it varied over both time and space, and even within the same rock type. For example the moisture content of samples that had been lying under snow for more than 24 hours ranged from 0. 10% to 1.13% for the same rock. He also identified the saturation coefficient as the best indicator of potential frost action. However, Hall (1987) found a significant difference between the response of 'massive' rock and 'intact' rock to mechanical weathering.

Hall and Hall (1991), m a senes of laboratory experiments on quartz-micaschist reproduced temperature and insolation regimes similar to those experienced on the island. They found that, although freeze-thaw cycles induced by changes in air temperature did not produce rates of change of temperature sufficient to cause thermal stress fatigue, values of up to7°C $rnin^{-1}$ occurred when the 'sun' was turned off Linear regression indicated that this rate of change could penetrate to a depth of approximately 2.2cm into the rock. However, they also pointed out that, because thermal stress fatigue and freeze-thaw operate within the same zone, it would be extremely difficult to discern the role played by either in rock breakdown.

3.1.2. Liv/11 ston Island

Livingston Island has a much higher level of precipitation (1000 to 1500mm, John & Sugden, 1971, cited in Hall, 1993) than Signy Island. The rocks are mainly volcanics interbedded with conglomerates and sandstones (Hall, 1993a citing Hobbs, 1968; Smellie et al., 1980). Wetting and drying was found to be the main weathering mechanism on the Northern aspect of the rocks whilst chemical weathering was evident on Southern aspects. Freeze-thaw was not common and might only be found where the rate of freezing during winter was slow enough to enable segregation ice to develop (Hall, 1993a).

3.2. ARID AREAS

The arid areas of Antarctica can be found within the Interior Antarctic Plateau (e.g. Thiel Mountains), Inland Mountain, Central Mountain (e.g. S0r Rondane Mountains) or Coastal Mountain Dry Valleys climatic zones of Campbell and Claridge (1987). They are characterised by large annual temperature ranges that fall to below -50°C in the cold central core of the Antarctic Plateau, and moisture regimes of as little as 15 to 20mm per annum.

3.2.1. Alexatrder Jsla11d

Although Alexander Island (Figure 1) is located within the Maritime Zone, the study site in Viking Valley is described as having a cold, dry, continental type climate (Hall, 1997a). The rocks are largely sandstone, conglomerates and argillaceous sediments (citing Taylor et al., 1979). A series of field experiments over two winters and one swnmer collected data on air, surface and inner rock temperatures (Hall, 1997a, b). Freeze-thaw weathering was very limited and most effective on the western to northern aspects where more moisture was available. Although there was no evidence of chemical weathering he found that the rate of change of temperature in the rock was far greater than 2°C per minute and concluded that thermal stress fatigue may be the dominant weathering process in this area. There was also evidence of wetting and drying and salt weathering (gypsum).

3.2.2. Adelaide b;/a11d

The study on Adelaide Island (Figure 1) measured rock temperatures at one-minute intervals on both the surface and at 2cm depth. The key result from this work was the gain in information on both freeze-thaw and thermal gradients that a one-minute data collection interval offered. For example, rates of change of temperature greater than the minimum estimated for thermal stress fatigue to occur were found in the one minute da-:ta, all:::: eit for very short periods, but were not evident in the 15 or 30 minute data in erval (Hall . 1998).

3.;2. .3. S. r Ronda11e Mountaill.J;

TbLe SlEtfr E.ondane Mountains (Figure 1) lie approximately 200km from the coast of East _A:ri1:arctia (Matsouka, 1995). Insolation is strong in summer generating frequent fre::::eze-:t-haw cycles at the ground surface and the mean annual air temperature is – 1g. 4°C_ The rocks are mainly gneiss, granite, amphibolite and diorite (Matsuoka, 19-95). Observations of scaling from rock walls and the disintegration of tuff blocks th '''t ha, been soaked in saline solutions and exposed to field situations were carried out ovr a 5-year period (Matsuoka et al., 1996). Effective freeze-thaw cycles (defined as the>se -w: ere the rock surface temperature rose above +2°C after falling below -2°C, 1:suok:=a, 1990b) exceeded 100 cycles per annum but bedrock shattering rates (<1%) we::Ie r:n ch lower than areas in the Northern Hemisphere that experienced much fewer fh:::: ze–t:l1aw frequencies (citing Matsuoka, 1991).

After 4 e>r 5 years exposure the blocks of tuff soaked in pure water or gypsum showed li e vı -1Jle breakage, whereas the thenardite blocks were significantly cracked and roL:arlded and the halite blocks were almost completely worn down. However, halite is alrr:::tost absent in these mountains and gypsum most common (Matsuoka, 1995). Whilst the=:re vv-:oa..s some evidence of chemical weathering, insolation weathering was not de rned ignificant.

J.r-4. ra Nova Bav

Loc::::;ated vvithin the Coastal Antarctic climatic region within Northern Victoria Land (F gure) by Campbell & Claridge (1987), French and Guglielmin (1999) found that fre ze-1l.aw was limited despite the relatively high number (50 per annum) of freeze-ilia- eye::. es that occurred, even at 2cm depth in the rock. Salts however, derived almost certainly ::fiom the sea, were plentiful. They concluded that traditional frost action was no the cl<>minant process of rock disintegration but that thermal stresses and/or salt we the __g may be the cause of the shattered rock and well developed taffoni and hoa-eyoor:I'1b weathering found there.

3 5. Tltiel ft# ;,.

Nolan Pillar (85°26'S, 86°46'W) is a small nunatak at about 1600m above sea level in the south-eastern-most part of the Thiel Mountains (Figure 1) in inland Antarctica (Ishimaru & Yoshikawa, 2000). They are characterised by extremely low temperatures (annual mean temperature -36°C, Rubin, 1962, cited in Ishimaru & Yoshikawa, 2000) and very little water. Three different weathering processes were observed, and investigated using optical microscopy, scanning electron microscopy and energy dispersive spectrometry. They concluded that the granular disintegration and micro-sheeting was a result of cracking of minerals due to the differential thermal stresses between quartz and plagioclase, and that the rock varnish was a result of oxidation.

4. KEY RESULTS FROM THE ANTARCTIC STUDIES

Overall the studies conducted in the Antarctic concluded that freeze-thaw, if important at all, is highly localised. For example, Hall (1997a, b) found that in the Viking Valley on Alexander Island, whilst there were sufficient temperature oscillations to produce freeze-thaw, lack of moisture meant it only occurred in the more moist western and northern aspects. Similarly, Matsuoka et al. (1996) put the low rates of bedrock shattering within the Sru Rondane Mountains down to the low moisture content of the rock (30-40%) rather than to any shortage of freeze-thaw cycles. On Livingston Island, however, whilst the moisture was sufficient for freeze-thaw to occur, rock temperatures rarely fell below 0°C and so again freeze-thaw was very localised (Hall, 1993).

Other effects of microclimate or microenvironment were also evident. For example Ishimaru and Yoshikawa (2000) concluded that the reddish brown varnish they found on rock surfaces was a relic of earlier warmer times when oxidation of minerals was possible due to snowmelt on rock faces. The insulation provided by snow could either prevent the thermal conditions necessary for freeze-thaw from occurring or slow down the cooling rate sufficiently to allow water migration and hence segregation ice and freeze-thaw to occur (Hall, 1993). Chemical weathering was greatly enhanced by the presence of snowpatches (Hall, 1993b). Even in arid areas wetting and drying could also be present, (Hall 1997a, b) and salt weathering was deemed to play a major role in the S0r Rondane Mountains (Matsuoka et al., 1996) but not in the Thiel Mountains (Ishimaru & Yoshikawa, 2000).

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1. INTRODUCTION

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According to Selby (1993) the most significant factors affecting the rate of weathering are climate and the physical and chemical composition of the parent rock and the most commonly recognised physical weathering processes are:

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Site factors are also important, especially the rate of soil drainage. However, rock break-up will only occur when the forces exerted are greater than the strength of the rock (Hall, 1987).

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2. DEVELOPMENTS IN THE NORTHERN HEMISPHERE

2.1. FREEZE-THAW

Initial theory on the freeze-thaw mechanism was based on the assumption that weathering was a result of the 9% expansion of water in either cracks (frost action) or between grains of rock (frost weathering) as it froze and subsequently thawed. Early experiments concluded that it was the frequency of these freeze-thaw cycles (i.e. crossings of the 0°C air temperature) that caused the rock to break down (e.g. Russell, 1943). However, subsequent studies showed that these cycles could be few or even absent in cold climate environments (Fahey, 1973) and the results of other research into intensity, rate (e.g. Lautridou & Ozouf, 1982) or type of cycle (e.g. Wiman, 1963) were inconclusive and/or contradictory. Some also noted that very small amounts of debris were actually produced during these experiments (Wiman, 1963; Potts, 1970; Brockie, 1972).

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2.2. SALT WEATHERING AND FREEZE-THAW

Salt weathering is believed to result from stresses in rock caused by the crystallization of salts in rock pores through either the growth of crystals from solution, thennal expansion or hydration (Selby, 1993; Fahey, 1985; Goudie, 1994), although other mechanisms have also been suggested (Williams & Robinson, 1991). The salts come either from the sea or inland lakes or are derived from the chemical weathering of the rock itself (Selby, 1993) and are widely recorded throughout the Polar Regions (Williams & Robinson, 1981), including Antarctica (Evans, 1970, cited in McGreevy, 1982). However, Selby (1993) noted that magnesium sulphate ($MgS0_4$) and thenardite ($Na2S0_4$) might be relatively uncommon in most inland deserts. A number of studies have cited the potential importance of salt weathering in cold environments, including Antarctica (e.g. Rodriquez-Navarro & Doehne, 1999).

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2.3. HYDRATION AND fl\ojSOLATION WEATHERING

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2.4. SUMMARY

In summary therefore, the Northern Hemisphere studies found no conclusive evidence that either freeze-thaw or salt weathering acting individually or together were effective mechanisms in rock disintegration nor was there clarity on how the mechanisms worked. Some continued to note that little debris was produced by freeze-thaw (e.g. Lautridou & Seppala, 1986; Tharp, 1987). In addition, with a few notable exceptions (e.g. Lautridou & Seppala, 1986; Fahey & Lefebure, 1988), these studies were primarily undertaken in the laboratory and on sedimentary rock, usually limestones or sandstones. Although the importance of temperature, moisture and rock properties was recognised there was no clear evidence as to which freeze-thaw cycle may be the most effective nor what type or concentration of salt. Little cognisance was taken of insolation weathering.

3. ANTARCTIC STUDIES

According to Campbell and Claridge (1987), whilst physical weathering is the dominant process of rock decay in Antarctica, its low moisture means that water based processes are not very effective there, freeze-thaw is comparatively restricted, and weathering is much less intensive than in the alpine or subalpine zones of more temperate areas. Salt weathering is stated as being the dominant process in the Dry Valleys but there is little evidence to indicate that insolation weathering was a significant mechanism. They also identified six different climatic regions.

Recent studies fall largely into two groups; those that have been conducted in the Maritime Antarctic and those that have been conducted in the more arid cold desert environments. Figure 1 indicates the main locations of these studies.

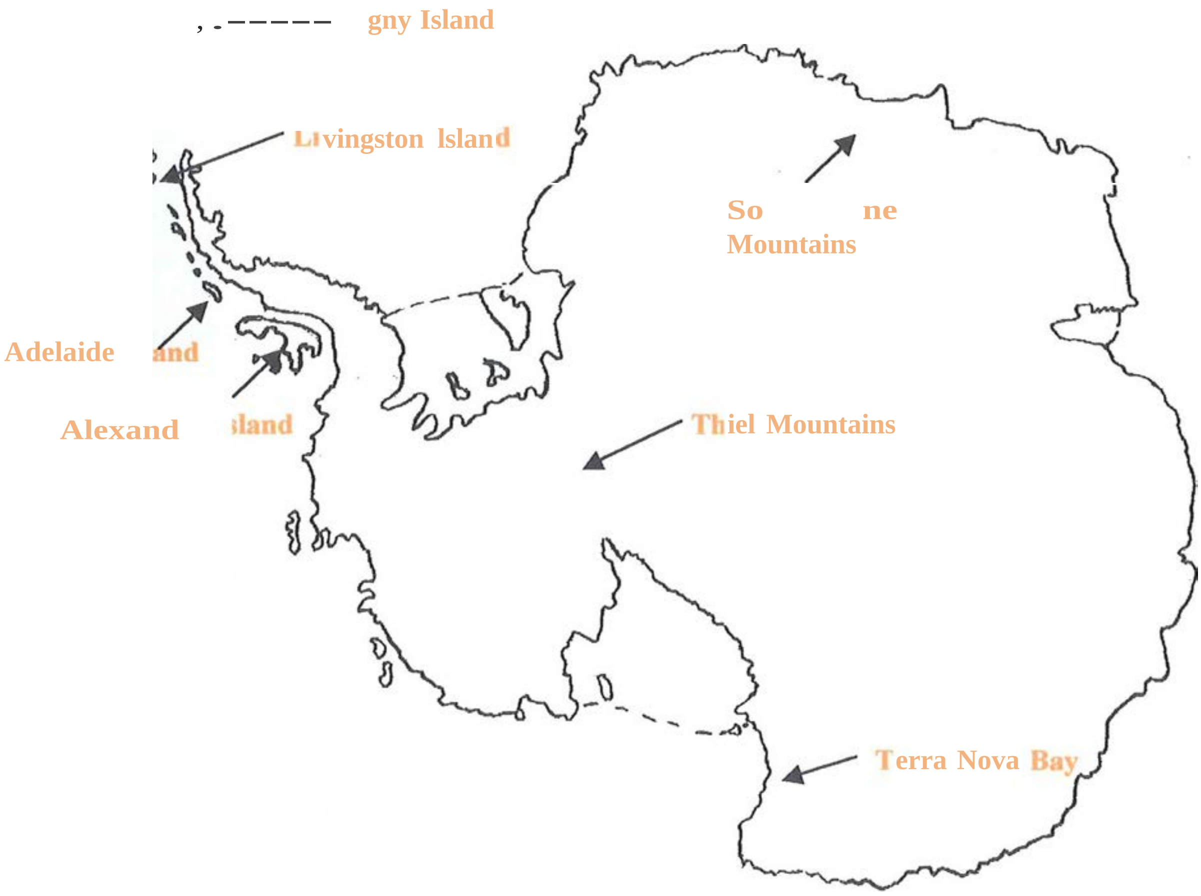

Figure 1. Antarctica, indicating the location of the different studies discussed in the text.

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Campbell and Claridge (1987) identified the Maritime Antarctic as the west coast of the Antarctic Peninsula and the islands north of 55°S. The temperature range is -12°C to +12°C with precipitation between 200 and 1000mm per annum. The soils are moist and ground temperatures may rise above freezing for short periods in any month of the year.

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A number of rock samples from different locations on Signy Island were tested and Hall (1986) found that moisture content was a major factor in rock weathering here but that it varied over both time and space, and even within the same rock type. For example the moisture content of samples that had been lying under snow for more than 24 hours ranged from 0.10% to 1.13% for the same rock. He also identified the saturation coefficient as the best indicator of potential frost action. However, Hall (1987) found a significant difference between the response of 'massive' rock and 'intact' rock to mechanical weathering.

Hall and Hall (1991), m a senes of laboratory experiments on quartz-micaschist reproduced temperature and insolation regimes similar to those experienced on the island. They found that, although freeze-thaw cycles induced by changes in air temperature did not produce rates of change of temperature sufficient to cause thermal stress fatigue, values of up to7°C min-[1] occurred when the 'sun' was turned off Linear regression indicated that this rate of change could penetrate to a depth of approximately 2.2cm into the rock. However, they also pointed out that, because thermal stress fatigue and freeze-thaw operate within the same zone, it would be extremely difficult to discern the role played by either in rock breakdown.

3.1.2. Livingston 1'0/and

Livingston Island has a much higher level of precipitation (1000 to 1500mm, John & Sugden, 1971, cited in Hall, 1993) than Signy Island. The rocks are mainly volcanics interbedded with conglomerates and sandstones (Hall, 1993a citing Hobbs, 1968; Smellie et al., 1980). Wetting and drying was found to be the main weathering mechanism on the Northern aspect of the rocks whilst chemical weathering was evident on Southern aspects. Freeze-thaw was not common and might only be found where the rate of freezing during winter was slow enough to enable segregation ice to develop (Hall, 1993a).

3.2. ARID AREAS

The arid areas of Antarctica can be found within the Interior Antarctic Plateau (e.g. Thiel Mountains), Inland Mountain, Central Mountain (e.g. S0r Rondane Mountains) or Coastal Mountain Dry Valleys climatic zones of Campbell and Claridge (1987). They are characterised by large annual temperature ranges that fall to below -50°C in the cold central core of the Antarctic Plateau, and moisture regimes of as little as 15 to 20mrn per annum.

2.1. Alexander Island

Although Alexander Island (Figure 1) is located within the Maritime Zone, the study site in Viking Valley is described as having a cold, dry, continental type climate (Hall, 1997a). The rocks are largely sandstone, conglomerates and argillaceous sediments (citing Taylor et al., 1979). A series of field experiments over two winters and one summer collected data on air, surface and inner rock temperatures (Hall, 1997a, b). Freeze-thaw weathering was very limited and most effective on the western to northern aspects where more moisture was available. Although there was no evidence of chemical weathering he found that the rate of change of temperature in the rock was far greater than 2°C per minute and concluded that thermal stress fatigue may be the dominant weathering process in this area. There was also evidence of wetting and drying and salt weathering (gypsum).

3.2.2. Adel ide Island

The study on Adelaide Island (Figure 1) measured rock temperatures at one-minute intervals on both the surface and at 2cm depth. The key result from this work was the gain in information on both freeze-thaw and thermal gradients that a one-minute data collection interval offered. For example, rates of change of temperature greater than the minimum estimated for thermal stress fatigue to occur were found in the one minute data, albeit for very short periods, but were not evident in the 15 or 30 minute data intervals (Hall, 1998).

3.2 3. Sar Roll 1 e Mou11taillS

The SBf Rondane Mountains (Figure 1) lie approximately 200km from the coast of East Antarctica (Matsouka, 1995). Insolation is strong in summer generating frequent freeze-thaw cycles at the ground surface and the mean annual air temperature is –18.4°C. The rocks are mainly gneiss, granite, amphibolite and diorite (Matsuoka, 1995). Observations of scaling from rock walls and the disintegration of tuff blocks that had been soaked in saline solutions and exposed to field situations were carried out over a 5-year period (Matsuoka et al., 1996). Effective freeze-thaw cycles (defined as those where the rock surface temperature rose above +2°C after falling below -2°C, Matsuoka, 1990b) exceeded 100 cycles per annum but bedrock shattering rates (<1%) were much lower than areas in the Northern Hemisphere that experienced much fewer freeze-thaw frequencies (citing Matsuoka, 1991).

After 4 or 5 years exposure the blocks of tuff soaked in pure water or gypsum showed little visible breakage, whereas the thenardite blocks were significantly cracked and rounded and the halite blocks were almost completely worn down. However, halite is almost absent in these mountains and gypsum most common (Matsuoka, 1995). Whilst there was some evidence of chemical weathering, insolation weathering was not deemed significant.

3 2 4. Terra Nova Ba '

Located within the Coastal Antarctic climatic region within Northern Victoria Land (Figure 1) by Campbell & Claridge (1987), French and Guglielrnin (1999) found that freeze-thaw was limited despite the relatively high number (50 per annum) of freeze-thaw cycles that occurred, even at 2cm depth in the rock. Salts however, derived almost certainly from the sea, were plentiful. They concluded that traditional frost action was not the dominant process of rock disintegration but that thermal stresses and/or salt weathering may be the cause of the shattered rock and well developed taffoni and honeycomb weathering found there.

5. Thiel Mountains

Nolan Pillar (85°26'S, 86°46'W) is a small nunatak at about 1600m above sea level in the south-eastern-most part of the Thiel Mountains (Figure 1) in inland Antarctica (Ishimaru & Yoshikawa, 2000). They are characterised by extremely low temperatures (annual mean temperature -36°C, Rubin, 1962, cited in Ishimaru & Yoshikawa, 2000) and very little water. Three different weathering processes were observed, and investigated using optical microscopy, scanning electron microscopy and energy dispersive spectrometry. They concluded that the granular disintegration and micro-sheeting was a result of cracking of minerals due to the differential thermal stresses between quartz and plagioclase, and that the rock varnish was a result of oxidation.

4. KEY RESULTS FROM THE ANTARCTIC STUDIES

Overall the studies conducted in the Antarctic concluded that freeze-thaw, if important at all, is highly localised. For example, Hall (1997a, b) found that in the Viking Valley on Alexander Island, whilst there were sufficient temperature oscillations to produce freeze-thaw, lack of moisture meant it only occurred in the more moist western and northern aspects. Similarly, Matsuoka et al. (1996) put the low rates of bedrock shattering within the Sm Rondane Mountains down to the low moisture content of the rock (30-40%) rather than to any shortage of freeze-thaw cycles. On Livingston Island, however, whilst the moisture was sufficient for freeze-thaw to occur, rock temperatures rarely fell below 0°C and so again freeze-thaw was very localised (Hall, 1993).

Other effects of microclimate or microenvironment were also evident. For example Ishimaru and Yoshikawa (2000) concluded that the reddish brown varnish they found on rock surfaces was a relic of earlier warmer times when oxidation of minerals was possible due to snowmelt on rock faces. The insulation provided by snow could either prevent the thermal conditions necessary for freeze-thaw from occurring or slow down the cooling rate sufficiently to allow water migration and hence segregation ice and freeze-thaw to occur (Hall, 1993). Chemical weathering was greatly enhanced by the presence of snowpatches (Hall, 1993b). Even in arid areas wetting and drying could also be present, (Hall 1997a, b) and salt weathering was deemed to play a major role in the Sm Rondane Mountains (Matsuoka et al., 1996) but not in the Thiel Mountains (Ishimaru & Yoshikawa, 2000).

The potential role of insolation weathering was stressed in several studies (e.g. Hall, 1998; Hall & Hall, 1991; French & Guglielmin, 1999) and in others cited as the predominant mechanism (e.g. Hall 1997a, b). The lack of mention of insolation weathering in the Northern Hemisphere literature was put down to other processes such as freeze-thaw or hydrolysis concealing it in the more temperate environments (Ishimaru and Yoshikawa, 2000). They concluded that thermal weathering must be responsible for the granular disintegration that occurred in the Thiel Mountains because the low temperatures and lack of salt and clay there ruled out the other mechanisms.

Hall (1997b) found that data collected at one minute intervals identified rates of temperature change that were greater than that required for thermal stress fatigue to occur.

The type of rock and its properties were also highlighted (Hall, 1986; Matsuoka, 1995). For instance, the location and concentration of quartz within a quartz-micaschist affected not only its strength but also its moisture content and hence potential vulnerability to frost action (Hall, 1986). He also found that moisture content varied over both time and space and even within the same rock type. Ishimaru and Yoshikawa (2000) observed that the rates of thermal expansion and the thermal conductivity for the quartz and plagioclase of the Nolan Pillar were very different and hence encouraged insolation weathering.

Hall (1992) stressed that processes worked synergistically and used the earlier work done on Signy Island to develop a series of flow charts detailing the different processes, their inter-relationships and the factors that controlled them. He produced a flow chart for each process, for example freeze-thaw (Figure 2), that included decision points, based on field and simulated data, to help identify the actual mechanisms involved.

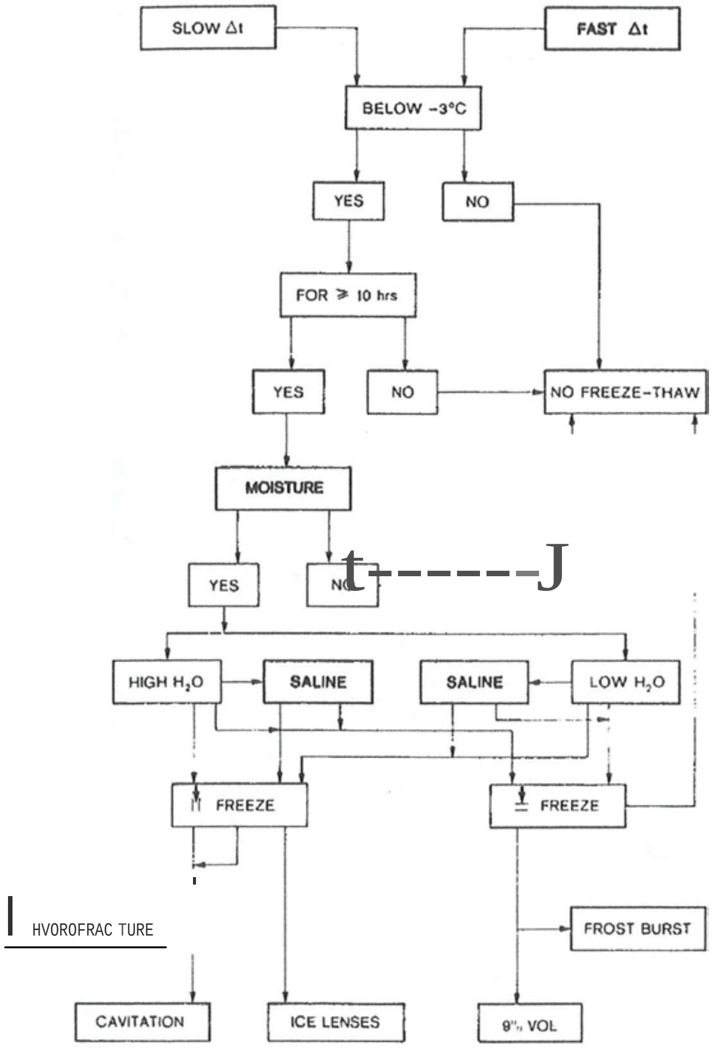

Figure 2. A flow chart offreeze-thaw weathering that allows deduction of the possible free ze-thmv mechanism. Source: Hall (1992, Figure 5.5).

Hall (1992) concluded that an element that controlled one process (e.g. temperature change for freeze-thaw) could also exert an influence on another process (e.g. thermal stress fatigue) and therefore the conditions that facilitated freeze-thaw weathering could also enable wetting and drying, salt and/or thermal fatigue to occur (Figure 3).

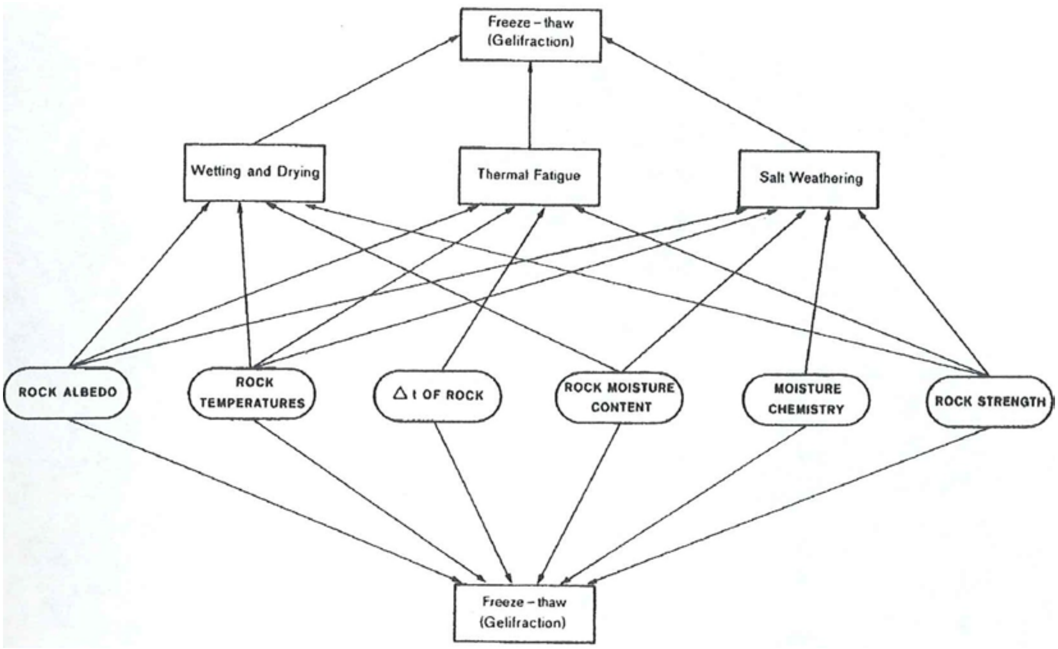

Figure 3. A flow chart showing the role of the controlling factors with respect to freeze-thaw and the other mechanical weathering processes. Source: Hall (1992, Figure 5.3).

Several studies identified some points of importance for laboratory experiments. For example Hall (1986) found that laboratory simulations sometimes exaggerated actual moisture contents (e.g. Fahey, 1983) and Matsuoka et al. (1996) suggested that the dominance of rock breakdown due to halite rather than thenardite in their field experiment was a result of the different temperature and humidity conditions used in the laboratory experiments. Hall (1987) found that the strength of quartz-micaschist depended on both the location of the quartz inclusions and whether the load was applied parallel or normal to schistosity. He also noted that, even if the moisture levels used by Lautridou and Ozouf (1982) in their experiments were available on Signy Island, temperatures there rarely fell below -8°C on other than a seasonal basis and hence the 500 cycles used in their experiments significantly exaggerated this real field situation.

With a few exceptions (e.g. Lautridou & Seppala, 1986; Fahey & Lefebure, 1988, Matsuoka et al., 1997) the Northern Hemisphere studies were conducted on sedimentary rocks and in the laboratory. The Antarctic studies on the other hand were conducted on a wide range of rocks, for example volcanics interbedded with conglomerates and sandstones (Hall, 1993); quartz-micaschist (Hall, 1986, 1987); dolerite (Hall, 1993) and tuff (Matsuoka et al., 1996), and usually in the field, either on the actual rocks themselves (e.g. Hall, 1997a, b; Matsuoka et al., 1996) or on rock

blocks exposed to the local environment (e.g. Hall, 1986; Hall, 1993) or by field inspections (e.g. French & Guglielmin, 1999).

Finally an analysis, albeit a not very rigorous one, of the literature reviewed between 1986 and 2000 found that whilst over 80% of Antarctic Studies referenced 5 or more Northern Hemisphere studies only 5% (1) of the Northern Hemisphere studies referenced 5 or more Antarctic studies. Most frequently there were no references (6) or just one or two (5 each).

5. CONCLUSION

The studies undertaken within Antarctica on rock weathering processes and mechanisms contain a wealth of information, primarily from fieldwork, on rock properties, temperatures and gradients as well as moisture, enabling an assessment of the effects of micro- as well as macroclimates or environments to be made. In the Northern Hemisphere however studies seem to have been largely conducted in laboratory conditions and on a relatively restricted set of sedimentary rocks. Several important implications for these laboratory studies have been highlighted by the work in Antarctica. The potential role of insolation weathering is also stressed.

Freeze-thaw is, in many cases, not recognised as being the predominant mechanism in Antarctica but rather one that operates only in very localised environments where the right combination of rock temperatures and moistures occur. Even where one mechanism may be found to dominate (e.g. Hall 1997a,b), a number of others were found to operate at the same time and in close proximity. Unfortunately there appeared to be little evidence that research in the Northern Hemisphere recognised the contribution that the Antarctic studies could make to the better understanding of rock weathering in cold climates.

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