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The Schmidt Hammer in geomorphological research

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Abstract: The Schmidt Hammer, originally designed for testing the hardness of concrete in 1948, was first used in a geomorphological context in the 1960s. Since then the advantages and disadvantages of the device for measuring rock characteristics have become apparent, and the Schmidt Hammer has been used for an increasing range of purposes, including the study of various weathering phenomena, the relationships between rock strength and landform, and for relative dating of a range of Holocene features. Readings of rock hardness have often been found to correlate well with other measures of rock character, such as uniaxial compressive strength and Young's Modulus of Elasticity.

Key words: relative dating, rock strength, Schmidt Hammer, weathering.

I Introduction

The purpose of this paper is to evaluate the contribution that the Schmidt Hammer has made to geomorphological research. The Schmidt Hammer (SH) was originally devised by E. Schmidt in 1948 for carrying out *in situ*, non-destructive tests on concrete hardness (Day and Goudie, 1977; Day, 1980). The SH has now been adopted by geomorphologists for a variety of reasons, including relative dating, the study of weathering phenomena, and the effects of rock strength on land forms (eg, Ericson, 2004).

The instrument measures the distance of rebound of a controlled impact on a rock surface. There are now several versions of the hammer.

- The one most used by geomorphologists is the 'N' type. It can provide data on a range of rock types from weak to very strong with compressive strengths that range from *c.* 20 to 250 MPa. A digital version, 'The Digi-Schmidt', is now available, though it is markedly more expensive.
- The 'L' type hammer has an impact three times lower than the 'N' type (0.735 compared to 2.207 Nm). It is appropriate for weak rocks and those with thin weathering crusts.
- The 'P' type is a pendulum hammer for testing materials of very low hardness, with compressive strengths of less than 70 kPa.

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When the SH is pressed against a surface, its piston is automatically released onto the plunger. Part of the piston's impact energy is consumed by absorption (ie, the work done in plastic deformation of the rock under the plunger tip) and is transformed into heat and sound. The remaining energy represents the impact penetration resistance (ie, the hardness) of the surface. This enables the piston to rebound. The distance travelled by the piston after it rebounds is called the rebound value (R). Harder rocks have higher R values (Aydin and Basu, 2005). Rebound values are influenced by gravitational forces to varying degrees so that non-horizontal rebound values must be normalized with reference to the horizontal direction (see Day and Goudie, 1977: Table 2). The R value is shown by a pointer on a scale on the side of the instrument (range 10–100).

Some workers have found that there is an inconsistency in the correction method proposed by the manufacturer in relation to the direction of rebound (Kolaiti and Papadopoulos, 1993). Aydin and Basu (2005) suggest that the reason for this is that the correlations provided by the manufacturer are derived empirically for a certain material (mostly concrete) with a relatively narrow range of mechanical properties and are often limited to two or four impact directions. They proposed alternative normalization methods.

There remains a wide variation in the recommended testing procedures employed by different researchers (Goktan and Gunes, 2005) particularly with regard to the number of impacts used to obtain 'R' values. For example, the ISRM (1978) recommended that one should record 20 rebound values from single impacts separated by at least a plunger diameter, and average the upper 10 values; Matthews and Shakesby (1984) recommended 15 rebound values for each sample, with 5 values that deviate most from the mean being discarded; and Katz *et al.* (2000) performed 32–40 individual impacts and averaged the upper 50%. Abnormally low values are omitted for a variety of reasons: they may relate to the fact that the rock was weakened by the actual impact of the hammer on the rock surface, or to small rock flaws that were not spotted visually before the impact was applied.

II Advantages and limitations

The SH has many advantages for geomorphological research, but for its effective use it is also necessary to appreciate that it has some limitations.

The advantages of the SH are:

- Portability (weighing between 1.7 and 2.3 kg).
- Cheapness (US$670 for a type N).
- Ability to make many readings *in situ* in the field.
- Lack of operator variance (Day and Goudie, 1977: Figure 15).
- Simplicity.
- Empirical evidence that R values correlate well with other rock properties.
- Calibration can be achieved easily with a test anvil (US$525).
- Temperature does not appear to have an appreciable influence on R values (Day and Goudie, 1977: 28).

On the other hand, the limitations of the SH are:

- It is extremely sensitive to discontinuities in a rock. Hence, fissile, closely foliated and laminated rocks cannot easily be investigated by this method.
- The test is sensitive to moisture contents, especially in weak rocks (Sumner and Nel, 2002).
- Results may be influenced by surface texture, with smooth planar surfaces giving higher readings than rough or irregular surfaces (Williams and Robinson, 1983). Surface irregularities are often crushed before the plunger tip reaches the main rock surface, resulting in some loss of impact energy. Both the magnitude and repeatability of hammer readings increases with the degree of surface polishing.
- There may be between-hammer variation and deterioration with age.

- The block mass of the rock to be tested is significant, and the test cannot be used on small, light blocks. Sumner and Nel (2002) suggest that block weight should exceed 25 kg for accurate and consistent rebound determinations.

It is therefore important that the Schmidt Hammer is used with care (McCarroll, 1987), and that it is properly calibrated. If the intention is to characterize unweathered rock, then the surface needs to be prepared by removing surface flakes, weathering resides and lichens with the carborundum which is supplied with the instrument.

III Schmidt Hammer rebound values and rock type

A very substantial number of R values has now been obtained from many different rock types in many parts of the world. A selection of values is given in Table 1. At one end of the scale 'weak' rocks such as chalk, aeolianite and marls have low values (*c*. 10). At the other end, silcretes, very hard limestones, quartzites, and various igneous rocks may have values that exceed 60, and very occasionally 70. On the basis of R values and other measures of rock strength, Selby (1993) has divided rocks up into 6 classes (Table 2). This provides a useful basis for classifying rocks and for giving a clear indication of a rock's character.

IV The 'R' value in relation to other rock property indices

Because of its speed, simplicity, portability, low cost and non-destructiveness, the SH has been used as a means of estimating other rock properties, such as compressive strength (Sendir, 2002). Various researchers have studied the relationship between rock compressive strength and SH R values, as shown in Table 3. The R^2 values range between 0.7 and 0.99 (Yaşar and Erdoğan, 2004). The regressions vary greatly between different rock types, however (Dinçer *et al.*, 2004), and so

Table 1 Schmidt Hammer values for selected rock types

Material	Mean R value	Source
Limestones		
Calcrete hardpans	42	Day and Goudie (1977)
Calcrete on chalk (Israel)	51–4	Yaalon and Singer (1974)
Travertines (Turkey)	35.2–57.0	Kahraman *et al.* (2004)
Chalk (Israel)	14	Yaalon and Singer (1974)
Maresha Chalk (Israel)	23.9	Katz *et al.* (2000)
Middle Chalk (UK)	20.0	Goudie *et al.* (1989)
Upper Chalk (UK)	9.0	Goudie *et al.* (1989)
Limestone aeolianite (Bahrain)	14.5	Day and Goudie (1977)
Calcarenite (Lord Howe Island)	19.8–28.6	Dickson *et al.* (2004)
Wind abraded dolomite (Bahrain)	50	Day and Goudie (1977)
Puerta Rico Aymamon limestone,		
unweathered	12.5	Day (1980)
case hardened	53.4	Day (1980)
Yucatan, Mexico, unweathered (Carillo Puerto)	35.9	Day (1980)
Browns Town (Jamaica)	32.1	Day (1980)
Montpelier Limestone (Jamaica)	20.50	Lyew-Ayee (2004)
Troy Formation (Jamaica)	41.87–55.23	Lyew-Ayee (2004)
Moneague Formation (Jamaica)	43.67–44.57	Lyew-Ayee (2004)
Chapelton Formation (Jamaica)	38.04–38.74	Lyew-Ayee (2004)
Somerset Formation (Jamaica)	41.76	Lyew-Ayee (2004)
Dolomitic Peten (Guatemala)	39.7	Day (1980)

(*continued*)

Table 1 Continued

Material	Mean R value	Source
Dolimitic (Belize)	39.8	Day (1980)
Melinau limestone (Mulu, Sarawak)	56.4	Day (1980)
Gunong Api pinnacle limestone (Mulu)	61.9	Day (1980)
Limestone with pinnacles (Mallorca)	52.7	Day and Goudie (1977)
Pliocene (Barbados)	29.8	Day (1982)
Miocene (Guadeloupe)	33.4	Day (1982)
Antigua formation (Antigua)	33.3	Day (1982)
Ceyhan (Turkey)	53.25	Yaşar and Erdoağn (2004)
Antique Cream	51.55	Yaşar and Erdoağn (2004)
Miocene oolitic (Budapest, Hungary)	18–23	Török (2003)
Cordoba Cream (Texas)	41.5	Katz *et al.* (2000)
Indiana Limestone (USA)	50.6	Katz *et al.* (2000)
Dolomite (Greece)	40–60	Sachpazis (1990)
Devonian (Napier Range, Australia)	55.9–56.6	Goudie *et al.* (1989)
Carboniferous (Buxton, UK)	51.0	Goudie *et al.* (1989)
Magnesian (UK)	35.0	Goudie *et al.* (1989)
Ancaster Freestone (UK)	30.0	Goudie *et al.* (1989)
Jurassic Bath Stone (UK)	15.0	Goudie *et al.* (1989)
Upper Cretaceous (Portugal)	38.0	Andrade *et al.* (2002)
Lower Cretaceous (Portugal)	39.0	Andrade *et al.* (2002)
Miscellaneous sedimentary		
Marls (Turkey)	17.5–44.6	Gökçeoğlu and Aksoy (2000)
Shale (Istanbul, Turkey)	30–64	Goktan and Gunes (2005)
Neogene mudstones (Japan)	10.5–32	Hayakawa and Matsukura (2003)
Mudstone (Ankara, Turkey)	27.1–38.6	Gökçeoğlu and Aksoy (2000)
Mudstone (Kaikoura, New Zealand)	32–35	Stephenson and Kirk (2000)
Pliocene and Miocene marls (Turkey)	<20–51	Basarir and Karpuz (2004)
Sandstone (Ankara, Turkey)	18.3–33.6	Gökçeoğlu and Aksoy (2000)
Sandstone (Handere, Turkey)	44.50	Yaşar and Erdoğan (2004)
Torridonian sandstone (Scotland)	43	Ballantyne *et al.* (1997)
Devea sandstone (Ohio, USA)	50.8	Katz *et al.* (2000)
Clarens sandstone (South Africa)	55	Sumner and Nel (2002)
Elliott sandstone (South Africa)	54	Sumner and Nel (2002)
Cambrian/Ordovician sandstones (SE Jordan)	41.0–44.7	Goudie *et al.* (2002)
Eocene Matjilla sandstone (California)	42.1	Duvall *et al.* (2004)
Eocene Sacate sandstone shale (California)	55	Duvall *et al.* (2004)
Gaviota (sandstone/shale) (California)	34.2	Duvall *et al.* (2004)
Vaqueros Oligocene sandstone (California)	22.7	Duvall *et al.* (2004)
Ashover Grit (Derbyshire, UK)	42.4	Williams and Robinson (1983)
Jurassic fine to medium grained sandstone (Alaska)	59	Whipple *et al.* (2000)
Jurassic siltstone/sandstone (Alaska)	46	Whipple *et al.* (2000)
Greywacke (Wellington, New Zealand)	24.0	Kennedy and Beban (2005)
Dolomite (Turkey)	55–59	Kahraman *et al.* (2004)
Silcrete (Botswana)	62.07	Day and Goudie (1977)
Sarsen Stones (England)	54.9	Day and Goudie (1977)
Upper Cretaceous marl (Portugal)	25	Andrade *et al.* (2002)
Carboniferous shale (Portugal)	27	Andrade *et al.* (2002)

(*continued*)

Table 1 Continued

Material	Mean R value	Source
Metamorphic		
Marble (Barbaros, Turkey)	54.80	Yaşar and Erdoğan (2004)
Marble (Osmaniye, Tukey)	47.42	Yaşar and Erdoğan (2004)
Marble (Carrara, Italy)	58.6	Katz *et al*. (2000)
Marble (Turkey)	48.3–58.0	Kahraman *et al*. (2002)
Marbles (Greece)	35–47	Sachpazis (1990)
Magaliesberg quartzite (South Africa)	62	Sumner and Nel (2002)
Precambrian quartzite (Botswana)	67.1	Day and Goudie (1977)
Migmatite (Kora, Kenya)	47.3–50.6	Pye *et al*. (1986)
Gneiss (Kora, Kenya)	49.4–53.5	Pye *et al*. (1986)
Quartz-Schist (NW Scotland)	48.2	Brook *et al*. (2004)
Gneiss/arenite/quartzite (NW Scotland)	45.7	Brook *et al*. (2004)
Gneiss (Yukon, Canada)	24–42	Brideau *et al*. (2004)
Biotite schist (S Alps, New Zealand)	51.5	Augustinus (1992b)
Greywacke/argillite (S Alps, New Zealand)	64.5	Augustinus (1992b)
Grey/Green schist (S Alps, New Zealand)	49.5	Augustinus (1992b)
Schist (Turkey)	40.0–43.7	Gökçeoğlu and Aksoy (2000)
Igneous		
Granite (Sierra Nevada, USA)	48–53	Ericson (2004)
Mt Scott granite (Oklahoma)	73.4	Katz *et al*. (2000)
Granite (Sweden)	55–56	Ericson (2004)
Cairngorms granite (Scotland)	66.5	Brook *et al*. (2004)
Granite (Shap, UK)	59.4–61.1	Day and Goudie (1977)
Salem granite (Namibia, Spitzkoppje)	59.4	This paper
Granite (Turkey)	55.7–62.5	Kahraman *et al*. (2002)
Roach Island tuff (Lord Howe Island)	23.4–31.8	Dickson *et al*. (2004)
Basalt (Turkey)	61.8–66.0	Kahraman *et al*. (2002)
North Ridge basalt (Lord Howe Island)	44.2–48.3	Dickson *et al*. (2004)
Vestfirŏir Peninsula basalt (Iceland)	67.3	Brook *et al*. (2004)
Basalt (N. Greece)	42.4	Aggistalis *et al*. (1996)
Marion Island basalt (Antarctic)	64	Sumner and Nel (2002)
Drakensberg basalt (South Africa)	62	Sumner and Nel (2002)
Toprakkale basalt (Turkey)	52.40	Yaşar and Erdoğan (2004)
Mount Lidgbird basalt (Lord Howe Island)	53.2–62.3	Dickson *et al*. (2004)
Ankara andesite (Turkey)	54–61	Karpuz and Paşamehmetoğlu (1997)
Gevanim syenite (Israel)	65.0	Katz *et al*. (2000)
Karoo dolerite (South Africa)	64	Sumner and Nel (2002)
Gabbro (N. Greece)	32.2	Aggistalis *et al*. (1996)
Gabbro/dolerite (Kora, Kenya)	47.7	Pye *et al*. (1986)
Cuillins gabbro/peridotite/granophyrne (Scotland)	67.9	Brook *et al*. (2004)
Diorite/Gabbro (S Alps, New Zealand)	61.1	Augustinus (1992b)
Granodiorite (Turkey)	57.0–63.3	Kahraman *et al*. (2002)
Dacite (Turkey)	43.75	Karakus *et al*. (2005)
Epidote-amphibolite (Turkey)	50.79	Karakus *et al*. (2005)
Diabase (Turkey)	62	Kahraman (2001)
Serpentine (Turkey)	59–62	Kahraman (2001)

Table 2 Approximate strength classification of rock

Description	Uniaxial compressive strength, MPa	Point load strength $I_{s(50)}$, MPa	Schmidt Hammer N-type, 'R'	Characteristic rocks
Very weak rock – crumbles under sharp blows with geological pick point, can be cut with pocket knife	1–25	0.04–1.0	10–35	Weathered and weakly compacted sedimentary rocks – chalk, rock salt
Weak rock – shallow cuts or scraping with pocket knife with difficulty, pick point indents deeply with firm blow	25–50	1.0–1.5	35–40	Weakly cemented sedimentary rocks – coal, siltstone, also schist
Moderately strong rock – knife cannot be used to scrape or peel surface, shallow indentation under firm blow from pick point	50–100	1.5–4.0	40–50	Competent sedimentary rocks – sandstone, shale, slate
Strong rock – hand-held sample breaks with one firm blow from hammer end of geological pick	100–200	4.0–10.0	50–60	Competent igneous and metamorphic rocks – marble, granite, gneiss
Very strong rock – requires many blows from geological pick to break intact sample	>200	>10	>60	Dense fine-grained igneous and Metamorphic rocks – quartzite, dolerite, gabbro, basalt

Modified from Selby, 1993: Table 5.3.

should be used only for particular lithologies (Sachpazis, 1990). Nonetheless, as Hack and Huisman (2002) point out, a large number of simple tests in the field, using the SH, will tend to give a better estimate of the intact rock strength at various locations than a limited number of more complex tests. Young's Modulus of Elasticity has been used in many geomorphological studies with a view, for example, to determining the effects of weathering processes on rock strength (eg, Allison, 1987). Values for Young's Modulus can be determined with the Grindosonic (a non-destructive electronic technique which measures the ultrasonic response of a regular-shaped sample, which has been struck to set up a mechanical vibration pattern within it), but various studies have indicated strong empirical relations between SH rebound values and measured Young's Modulus (Katz *et al.*, 2000), with R^2 values as high as 0.99 (Table 3) (see also Sachpazis, 1990; Aggistalis *et al.*, 1996).

In addition to compressive strength and Young's Modulus, attempts have been made to determine the correlation between R values and other measures of rock physical properties, including the point load index (Aggistalis *et al.*, 1996) and the Shore Scleroscope (Yaşar and Erdoğan, 2004). R values are also one of the components of rock mass strength classifications (Selby,

Table 3 Correlation between Schmidt Hammer hardness with uniaxial compressive strength (UCS) and Young's modulus *(E)*

Equation	R^2	Researcher	Lithology
UCS			
$UCS = 6.9 \times 10^{[0.0087\gamma N+0.16]}$	0.94	Deere and Miller (1966)	varied
$UCS = 6.9 \times 10^{[1.348 \log(\gamma N) - 1.325]}$	–	Aufmuth (1973)	varied
$UCS = 0.447 \exp[0.045(N + 3.5) + \gamma]$	–	Kidybinski (1980)	coal, shale, mudstone
$UCS = 2N$	0.72	Singh *et al.* (1983)	sandstone, siltstone
$UCS = 0.4NLM - 3.6$	0.94	Sheorey *et al.* (1984)	coal
$UCS = 0.994N - 0.383$	0.70	Haramy and De Marco (1985)	coal
$UCS = 0.88N - 12.11$	0.87	Ghose and Chakraborti (1986)	coal
$UCS = 702N - 1104$	0.77	O'Rourke (1989)	sandstone
$UCS = 4.3 \times 10^{-2}(N\gamma_d) + 1.2$	–	Cargill and Shakoor (1990)	carbonates, sandstones
$UCS = 1.8 \times 10^{-2}(N\gamma_d) + 2.9$	–	Cargill and Shakoor (1990)	carbonates
$UCS = 2.208e^{0.067N}$	0.96	Katz *et al.* (2000)	limestone, sandstone
$UCS = \exp(0.818 + 0.059N)$	0.98	Yilmaz and Sendir (2002)	gypsum
$UCS = 2.75N - 36.83$	–	Dinçer *et al.* (2004)	andesites, basalts, tuffs
$UCS = 2.22N - 47.67$	–	Aggistalis *et al.* (1996)	gabbros, basalts
E			
$E = 6.95\gamma^2 N - 1.14 \times 10^6$	0.88	Deere and Miller (1966)	varied
$E = 6.9 \times 10^{[1.06 \log(\gamma N) + 1.86]}$	–	Aufmuth (1973)	varied
$E = 0.00013N^{3.09074}$	0.99	Katz *et al.* (2000)	syenite, granite
$E = \exp(1.146 + 0.054N)$	0.91	Yilmaz and Sendir (2002)	gypsum

UCS = uniaxial compressive strength (MPa), *E*: Young's modulus (MPa), *N*: Schmidt Hammer rebound number, γ: rock density (g/cm^3).
Source: From Yaşar and Erdoğan (2004): Table 1, with additions.

1980; 1982), along with the state of weathering, various joint characteristics and the presence or otherwise of water seepage from the rock face.

V The Schmidt Hammer as a dating tool

The SH can be used to indicate the degree of weathering that a rock has undergone. Intuitively, there should be a relationship between degree of weathering and the length that the rock surface has been exposed to weathering attack. This is the basis upon which the SH has been used to estimate relative ages of various geomorphological phenomena (see Table 4), including glacial moraine, rock glaciers, mass movements, talus, raised shorelines and platforms, and anthropogenic features. The technique was pioneered by Matthews and Shakesby (1984).

The relative dates obtained by this method can be compared with other relative dating techniques such as weathering rind development, clast angularity, soil development, lichenometry, etc, or compared with C^{14} dating and archival data (Matthews *et al.*, 1986). It is possible that in the future the SH may help to identify sites that are suitable for cosmogenic nuclide studies.

SH dates often show considerable variability, partly because of local microclimatic differences, including the influence of late-lying

Table 4 Examples of the use of the Schmidt Hammer for relative age dating

Southern Alps (NZ)	Differentiate Little Ice Age moraines	Winkler (2000)
Breheimen (S. Norway)	Holocene moraine sequences	Shakesby *et al.* (2004); Winkler *et al.* (2003)
Southern Alps (NZ)	Holocene moraine sequences	Winkler (2005)
Sunnmore (Norway)	Rock-fall avalanche deposits	Nesje *et al.* (1994)
Lake Superior (Canada)	Anthropogenic pits	Betts and Latta (2000)
Nepal Himalaya	Holocene moraine sequences	Shiraiwa and Watanabe (1991)
Faroe Islands	Rock glaciers	Humlum (1998)
Swiss Alps	Rock glaciers	Frauenfelder *et al.* (2004; 2005)
Marion Island	Glacial history	Sumner *et al.* (2002)
Boyabreen (W Norway)	Holocene moraine sequences	Aa and Sjåstad (2000)
Iceland	Holocene glacial sequences	Evans *et al.* (1999)
Cederberg Mountains (South Africa)	Debris flow deposits	Boelhouwers *et al.* (1999)
La Sal Mountains (Utah, USA)	Rock glaciers and lakes	Nicholas and Butler (1996)
Leirbreen (S Norway)	Neoglacial moraines	McCarroll (1989a)
Jotunheimen (S Norway)	Neoglacial moraines	McCarroll (1989b)
Jotunheimen (S Norway)	Lake shorelines and platforms	Matthews *et al.* (1986)
Japanese Alps	Rock glaciers	Aoyama (2005)
Lake District (NW England)	Rock avalanches	Clark and Wilson (2004)
Tunisia	Alluvial fans	White *et al.* (1998)
NE Greenland	Deltaic deposits	Christiansen *et al.* (2002)
E Greenland	Glacial deposits	Lillieskold and Sundquist (1994)
Sweden	Raised beaches	Sjöberg (1990)

snow patches in certain topographic situations. For this reason, some workers only take readings on ridge crests (eg, Aoyama, 2005) and over small altitudinal ranges (White *et al.*, 1998). It is also important to be aware of the limitations of the SH technique itself because of factors such as surface roughness of boulders (McCarroll, 1989a; 1989b; 1991), and variability in weathering rates between different lithologies and mineralogies. In any one area, only the same rock types should be tested because different original surface hardness and weathering resistance will affect the SH measurements (Winkler, 2005).

In some locations, SH dating has not been found to be very effective at differentiating among depositional episodes, and other measures, such as weathering rind development, have been found to be more useful (Nicholas and Butler, 1996). Elsewhere, the SH has been shown to be a successful technique in comparison with some others, but plainly the combined use of various techniques is likely to be superior to the use of one technique in isolation (Boelhouwers *et al.*, 1999). Evans *et al.* (1999) found that the success of the SH technique in dating Icelandic moraines was influenced by geomorphological setting. Areas subject to surging glaciers and reworking of moraines by debris flows are likely to be problematical. Moraines constructed in areas of debris flow activity will inevitably contain boulders of various ages, comprising both those released from older features and those released directly by the receding glacier. Glacier snouts that have advanced unrestricted into lowland terrains produce smaller moraines that are less subject to reworking than those in higher relief situations (Evans, 1997). In the case of Alpine rock glaciers, Frauenfelder *et al.* (2004) found that SH dates correlated well with chronologies estimated from photogrammetric stream-line interpolations.

The resolution of SH dating is variable. On the one hand, there are those that believe that the maximum resolution can be *c.* 200–300 years (eg, Winkler, 2005); while, on the other hand, there are those who have found it is only useful for distinguishing sites deglaciated during the Little Ice Age from those deglaciated during the Lateglacial and early Holocene (McCarroll and Nesje, 1993).

VI The Schmidt Hammer and weathering

In addition to using degree of boulder weathering as a basis for relative dating, the SH has had a number of roles in the study of weathering *per se*.

1 Changing rates of weathering through time

There is considerable controversy about the relationship between rock weathering and time, and whether rates are linear or non-linear (Colman, 1981) Studies of alluvial fan segments in Tunisia have indicated that rates are not constant but decrease over time (White *et al.*, 1998). Sjöberg and Broadbent (1991) were able to obtain a measure of how weathering developed through time by examining raised beaches at different elevations in Sweden, and found a correlation of 0.96 between elevation of the beaches and their R values.

2 Aspect effects

Differences in SH readings with aspect give an indication of the extent to which aspect is a factor in determining degree and rate of weathering (Hall, 1993; Waragai, 1999). Associated with this is the extent to which snow patches in periglacial areas modify weathering rates (Ballantyne *et al.*, 1989; 1990; Benedict, 1993; Grab *et al.*, 2005). There is scope to examine the effects of aspect-controlled differences in moisture content in arid areas on rock weathering.

3 Tafoni

Tafoni (cavernous weathering forms) have also attracted users of the SH. Matsukura and Matsuoka (1996) found that larger tafoni developed on bedrock with smaller R values (eg, on tuffs and conglomerates) and that smaller tafoni developed on those rocks with larger R values (eg, on basalt, andesite, granite and sandstone). Matsukura and Tanaka (2000) found that the values on the backwall and ceiling of tafoni are smaller than those on the visor and outside the tafoni, while Mellor *et al*. (1997) found R values were significantly higher on the outer roof of Spanish tafoni than on the inner cavern walls. Hall (1997) found that in Antarctica tafoni size and occurrence was related to differences in weathering with aspect. In Jordan, Goudie *et al*. (2002) used the SH to identify the significance of case hardening in tafoni development.

4 Karstic forms

Karstic phenomena are intimately connected to rock properties and various studies have related different karst morphological types to limestone hardness as measured with the SH (Day, 1981; Haryono and Day, 2004). Case hardening of limestone outcrops affects the morphology of tropical karst types such as cockpits and towers, as the pioneering work of Monroe (1966) demonstrated. The degree of case hardening and the strength of calcretes has also been determined (Yaalon and Singer, 1974). Sometimes such differences in hardness cannot be seen through visual inspection (Day, 1980).

The changes in hardness brought about by case hardening can be considerable. In Puerto Rico, Day (1980) found that case hardening extends to 2 m into the rock and the R values of the case hardened zone are in excess of 50, whereas those of the unaltered bedrock average 12.5. In Jamaica's Cockpit Country, Lyew-Ayee (2004) found that fresh Montpelier limestone had R values that averaged as little as 14, whereas the case hardened zones had values as high as 38. This enabled towers to form in what was otherwise a very weak material. Day (1980) also found that in Sarawak karst pinnacles largely developed on the hardest limestones which, he surmised, are those most able to support such fragile features. Similarly, in NW Australia, Goudie *et al*. (1989) found that rillenkarren were superbly developed on hard limestones (R values from 46 to 64).

5 Inselbergs
The question of lithological controls on the development of inselbergs has long intrigued geomorphologists. In the Kora area of central Kenya, Pye *et al*. (1986) took SH readings on rock outcrops with and without inselbergs. They found that all rock types in the area, whether or not they developed inselberg forms, had similar R values and concluded that differences in resistance to weathering and erosion were not due to variations in rock hardness but to their potassium feldspar content.

6 Weathering classifications
The SH can be used to give a quantitative value for degree of rock weathering. An example of this, for Turkish andesites (Karpuz and Paşamehmetoğlu, 1997) is given in Table 5. In Calabria, Italy, Le Pera and Sorriso-Valvo (2000) were able to relate R values and a weathering classification to the biotite content of granites.

7 The role of subaerial weathering in shore platform development
Arguments exist in the literature about the processes that mould shore platforms. Is wave attack or subaerial weathering (by such processes as wetting and drying, salt weathering and frost attack) the dominant mechanism? Stephenson and Kirk (2000), working in New Zealand, found by using the SH that weathering had indeed occurred and had reduced rock strength by up to 50%. They concluded that wave processes cannot alone cause the development of shore platforms at Kaikoura. The SH has not yet been applied to the study of beachrock evolution, but this is a field where there is scope for investigation.

8 Case hardening on buildings
Because of sulphation and other effects, the hardness of building stones may vary because of the development of weathering crusts composed of such minerals as gypsum and calcite. Török (2003) investigated crusts on limestone buildings in Budapest, Hungary, using both the SH and Duroscope rebound tests, and found significant differences in hardness between the host rock and its weathering crusts.

9 Degree of weathering above and below glacial trimlines
Degree of weathering is helpful in the identification of nunataks, trimlines and glaciation extent, and the SH can be used for this purpose (Ballantyne *et al*., 1997; Anderson *et al*., 1998; Rae *et al*., 2004). R values are lower above the glacial limit because of periglacial weathering.

VII Rock mass strength

As already mentioned, R values are incorporated in some rock mass strength (RMS) classifications, and various attempts have been made to see the relationship between RMS and landforms. For example, in a coastal study Trenhaile *et al*. (1998) were able to test whether there was any difference in properties between coastal stacks in the Bay of Fundy (Canada) and adjacent platforms and cliffs. They found no such difference. On the other hand, Dickson *et al*. (2004) found the SH was useful for assessing the influence of rock resistance on the coastal morphology of Lord Howe Island in the SW Pacific.

More generally, a RMS Classification involving the SH was used in the Napier Range of NW Australia by Allison and Goudie (1990). They identified seven main slope forms associated with different facies of a Devonian reef and found that it was possible to draw associations between slope profile shape and RMS. Equally, Synowiec (1999), working in SW Poland on sandstone slopes, found a strong correlation between slope angle and RMS. In Central California, Hapke (2005) found some relationship between the yield of sediment from landslides and the R values of the catchments from which they were derived.

Table 5 A scale of rock mass grades and weathering stages of Ankara andesites

Rock mass grade	Material weathering stages	Description	R value
Rock			
I	Fresh	No visible sign of rock weathering. Discoloration of the rock material, long discontinuities and penetration, inward from discontinuity surface	54–61
II	Slightly stained		39–54
Rock and soil			
III	Completely stained	Complete discoloration of the rock material and weakening of rock-mass by opening of grain boundaries and increase in discontinuity spacing, having less than 50% soil between joint bounded blocks	54–61
IV	Weakened	Complete discoloration of rock material and weakening of rock-mass by increase in opening of grain boundaries and spacing with infilling of more than 50% of rock by weathering products	18–28
Soil			
V	Disintegrated and decomposed	Intact, friable soil	<18
VI	Soil		

Modified after Karpuz and Paşamehmetoğlu (1997): Tables 3 and 4.

Attempts have been made to assess glacial trough morphology in relation to SH values, most notably by Augustinus (1992a; 1992b) in the Southern Alps of New Zealand and by Brook *et al*. (2004) in the Scottish Highlands and NW Iceland. In all three areas, there was found to be a clear relationship between RMS and trough form. Brook *et al*. found that valley cross profiles formed on bedrock with a high RMS were steep and narrow because valley form modification by glaciers was less rapid or effective. In contrast, valleys developed in rock with a lower RMS value were wider and more U-shaped, indicating a higher degree of glacial modification.

River channel form, both in terms of cross and long profiles, is a topic of increasing interest (see, for example, Whipple *et al*., 2000; Snyder *et al*., 2003; Duvall *et al*., 2004). Mitchell *et al*. (2005) found that in the Colorado River R values correlated significantly to channel width and gradient. In Idaho, Lifton *et al*. (2005) found a strong negative correlation existed between R values and valley width, with wide valley floors corresponding to weak bedrock, and narrow valley floors with strong bedrock. The also found a statistically significant difference in R values between north- and south-facing slopes, indicating that aspect affects weathering intensity and bedrock strength. In Japan, Hayakawa and Matsukura (2003) investigated the relationship between recession rates of waterfalls and various rock properties, including SH R values.

VIII Conclusion

Since it was first developed over five decades ago as a means of assessing the hardness of concrete, the SH has been found to have an increasing range of applications in geomorphological research. It is a convenient means of establishing rock hardness in the field, providing that certain precautions are taken in the light of its known limitations. Portable, cheap, free from operator variance, simple, easily calibrated and free from any noticeable temperature effects, it can with due care produce rock hardness values that correlate well with such parameters as uniaxial compressive strength or Young's Modulus of Elasticity. By providing, quite rapidly, a large number of tests in the field, the SH may in the end give a better estimate of the intact rock strength at various locations than a limited number of more complex and laboratory based techniques. It can, of course, be used alongside other techniques to provide a more rigorous and robust characterization of rock properties, and to that end R values are one component in RMS characterizations. If geomorphologists are going to understand how rock type influences relief in a more quantitative manner than is usual, the SH can play a role.

The SH has now been extensively used for relative dating of mainly Holocene landforms, including moraines, rock glaciers and mass movement phenomena. It has also been proved to be a valuable tool for assessing the rates at which weathering takes place through time, the extent to which weathering is affected by aspect, the nature of tafoni, the form of karstic landforms, the role of case hardening on natural rock outcrops and on buildings, the lithological control on inselberg formation, the classification of weathering residues, the role of weathering in shore platform development, and in the delimitation of glacial limits. It is also becoming evident that rock mass strength studies involving the SH can throw light on such diverse phenomena as glacial troughs, river channel profiles, slope forms and coastal morphology.

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