The mathematical characterization and dating of old dry limestone field walls

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Abstract
Ground movements are considered to cause small-scale sinuous deviations from linearity of dry limestone field walls. These deviations have been measured in an attempt to assess the age of a wall. The weight of a wall is a major factor counter-acting movement. The sinuosity data coupled with wall weight can be correlated well with known wall ages despite the many caveats. This allows extrapolation to estimate the ages of much older walls subject to a quantifiable degree of uncertainty. The correlation is based on one locally common type of wall which shows little change in construction method over centuries.

Age-related characteristics of dry-stone field walls might help to establish or confirm old boundaries and to determine the gradual development of fields from early times. Good examples are given by Hodges in his account of the history of Roystone Grange in Derbyshire, by Beaumont for Hebden in Wharfedale and Lord for Winskill in Langcliffe parish near Settle. The objective of this exploratory project is to determine if statistical evaluation of small-scale sinuosity in plan view of a limestone dry-stone wall can be used to assess its approximate age. This sinuosity is considered to be the net result of the presumed random processes of ground movement and decay together with the counter-effects of occasional repair and resistance due to wall weight.[1]

The study has been carried out in Langcliffe parish in Craven in North Yorkshire, which was created from the ancient parish of Giggleswick in the mid-1800s and was a manor held by Sawley Abbey who owned it until Dissolution in 1536. Lancaster notes that in 1251 the tenants of Sawley Abbey and Fountains Abbey were in dispute about Stainforth and Langcliffe moors and the wandering of animals on to each other's grazing. The quarrels only reached written resolution in 1279. Some boundaries may date from this period since the texts contain the phrases 'outside the wall', 'enclosed meadow' and 'escape across the bound'. The word fence (associated with the word defence) is used in documents, sometimes meaning a hedge, but in northern areas stone walls are clearly meant, as in the Langcliffe Enclosure Act of 1789. Muir quotes Enclosure using a 'fence wall, 5ft 9 inches high'. In 1822 Baines remarked that 'The situation of Settle is picturesque, but its beauty would be much increased if the high and gloomy stone fences round the fields were displaced by hawthorn hedges.' [2]

Nearly all the walls in Langcliffe parish are of limestone and might be roughly classified as being built in the monastic period up to 1536, in the absentee landlord period when the Darcy family held the manor up to 1591, in the period of 17th- and 18th-century land transactions after the sale of the manor of Langcliffe to feoffees in 1591, at the time of the Enclosure Act and Award (1789, 1793) in the railway period of the 1870s, or very recently. We have documents concerning the families who bought properties in 1591 at Winskill (a set of farmsteads in the parish) which help to establish the boundaries of four main farms at that time. Many private land transactions were made in the 1600s. We have maps for land enclosed in 1756 at Settle Banks (just south of the Langcliffe parish border), for the enclosure of the high pastures in 1793, for the Tithe Assessment of 1844 (map of 1841), for a land transaction in 1845 for Brown Bank at Winskill, for G.A. Paley's estate in 1920, and 6 inch OS maps for 1845, 1893, 1898, 1909, 1910, and 1954. So certain walls can be given a minimum likely age. We acknowledge that early walls may not be as old as a boundary line and might have been rebuilt on occasion but on the same foundations; we consider that most walls of post-18th-century dates can be securely dated and that these can form a good basis for a correlation of age as described below and allow reasonably good prediction of age for older walls. [3]

Currently typology is used to date walls roughly if no map or documentary evidence is available and a more objective method is sought to support such an approach. Lord has developed a method of characterizing limestone walls at the National Trust Estate at Malham and elsewhere and proposes a typology as follows:

1. Double-sided walls with wide tops (0.5m or more) and near vertical sides usually at least 1.6m high; or narrow tops (0.4m) with battered sides. The double-sided narrow-top walls can be sub-divided into those with irregular through-stones or regular throughs in two to four rows. The latter are not found in Langcliffe. Smaller stones are used to infill; earth would entrap water with consequent problems with frost heave.

2. Much less common three-quarter double-sided walls with mainly deep stones running right across the width of the wall interspersed with pockets of opposing face stones. Filling stones are hardly ever used in the middle of the wall. They are built with little batter. However, they are narrow-top and so represent a more economical use of walling stone.

3. Single-sided walls, also uncommon.

The fields at Winskill have some early wide-top walls, which probably became obsolete by 1591 (the manorial sale date), and later walls are narrow-top. [4]

The coping stones may be laid flat and sometimes protruding (early walls), or sloping (later walls). Large up-ended slabs (orthostats) and large boulders are often found in early walls. It seems reasonable to suggest that early wall builders would naturally think that near-vertical sides were sensible, particularly if stones were locally abundant and field clearance was advantageous. Maybe there was a later realization that sloping-side construction required fewer stones, that the centre of gravity was lower, and the wall just as stable. Even later came the understanding that through-stones used to bind the two sides of a wall enhanced strength and many such walls were built in the Dales late in the 18th century and thereafter. Fothergill illustrated a wall with coursed through-stones typically seen during his tour in 1805. However, the general lack of obvious through-stones (not readily available locally) for walls of all ages in Langcliffe parish is notable. In neighbouring parishes flaggy gritstone or slate is available and used for through-stones. There was no change in Langcliffe to a construction method using coursed throughs in the 18th century. Figure 1 shows the nature of local walls. The National Stone Centre at Wirksworth in Derbyshire has many examples of wall types from all over the UK but in modern styles.[5]

Where did all the stones needed to build the walls come from? For typical wall dimensions one can calculate what volume of stones is needed to surround a field of specified size and shape. It is estimated that for the walls of a square field of one hectare (100m by 100m) sufficient stones of a sensible size would have occupied only about 10% of the field surface, even less for a larger field. Field clearance of stones into heaps (a few extant) is a likely original source of the stones; in addition there are in many Langcliffe fields small quarries on limestone outcrops from which stones could be levered out. Some screes of broken rock exist.

Fig1 North Goose Scar

The factors affecting wall stability and the difficulties of measurement are manifold as discussed by Lord. A very old wall might be very irregular in height and linearity due to slumping (spreading of the base), buckling on a down-slope, or partial collapse and this irregularity may be an indication of age. A wall will have been mended at various times but the same stones were probably re-used to give a wall of about the same height as the original. Walls fall down repeatedly in the same place. Large basal boulders are not likely to have been moved. In Langcliffe there are examples where stones have been robbed from decayed walls to build newer ones and some now-derelict walls were in existence in 1841, indicating that decay can be rapid.[6]

Wall heights

Richard I may have required his tenants to limit their hedgerows to a yard and a half high so that deer could jump over them. However, neither the Carta de Foresta of Canute nor that of Henry III are specific about fence heights (Manwood). In 1564 a Giggleswick by-law quoted by Brayshaw and Robinson required tenants to make the out-dykes a yard and a half high. Winchester quotes orders made for Shap in 1592 and 1621 to 1639 for stone walls 'foure foot high'. Raistrick states that some local 18th-century Enclosure Acts specify construction 6 feet high and 34 to 36 inches wide at the base, and others specify six quarter yards high with an additional quarter yard of capstones, i.e. seven quarter yards totalling 63 inches (5.25ft or 1.60m). The local (in Langcliffe) pole length was 7 yards rather than the statute 5.5 yards – a quarter of the local pole is seven quarter yards. The Langcliffe Enclosure Award of 1793 for the high rough grazing land states that fences (walls) should be two yards high and kept in good repair for ever against trespass of sheep and cattle. They had to be built by November 1794. The award does not specify the use of through-stones. A common specification elsewhere quoted by Garner and Winchester is 3ft 9 inches plus 9 inches for the capstone totalling 4ft 6 inches, i.e. a yard and a half. Mitchell says that where sheep were kept walls were to be 'six quarters in height with an additional quarter by way of capping' and in Durham usual dimensions were 4ft high plus a coping of 9 inches. The park walls at Ravenstonedale near Kirkby Stephen were required to be 12 feet high as seen on a map of 1560/1. In Scotland an enclosure wall height of one ell with a peat coping was specified in mid-18th century (37 inches in this case – the ell is somewhat variable in length).[7]

Containment of cattle or sheep requires different wall heights – a 'cow wall' being 4ft, and a sheep wall 5ft (Garner). Keeping out wolves might have been a consideration in medieval times. Rainsford-Hannay records that stones were to be 'taken from within, as long as there are any...' and 'not to leave a stone in the enclosure, which three men can roll or four men carry in a hand barrow'. The wall was later to be raised to 55 inches using stones which arose after ploughing.[8]

The base width is roughly half the height, and is variable locally. A trench about one spade deep was dug for the footings and it is presumed that this depth was part of the specified height. It is clear that a national standard was not set up at any time and that farmers made their own field walls of any height they thought appropriate.

Measurement and characterization of wall heights

Is wall height irregularity alone an indicator of age? A selection of walls of different ages was chosen – with a base of about 80cm and top width of about 40cm. They are similar in construction and sit on rough grazing land, not solid rock. The measurements were made every 2m using a 2m rigid stick marked every 5cm for height measurement. The height was measured from the ground level of the wall but is generally likely to be too low a measurement. Hygiene (specifically *E. coli. O157*) is an issue in fields used by cows.

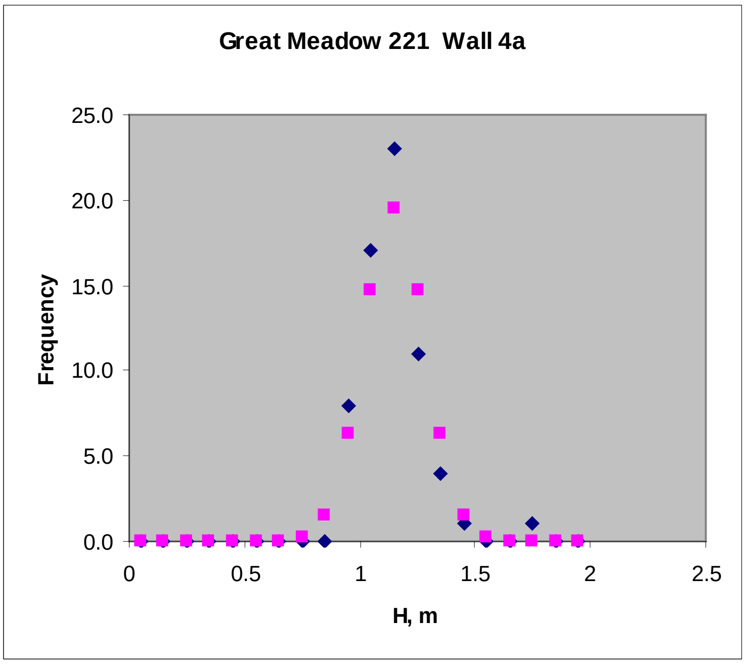


Fig 2 Normal distribution

The distribution of heights is random and fits a Normal distribution as typified by Figure 2. A measure of the variation in height is expressed as the population standard deviation on height, σ_h, which is readily calculated (see Appendix 1). The current mean height of these walls is 1.47m and the standard deviation is 0.16m, i.e. 68% of the data lie between 1.31m and 1.63m (excluding the decayed wall Lower Claypitts 193). There are no relationships apparent between height and population standard deviation or deviation and age (data in Tables 1 and 2). Nevertheless, height data are needed in estimating wall weight used in correlating ages with sinuosity as discussed below. A quoted requirement of 15cm for the depth of footings brings height up to an average of 1.6m (seven quarter yards). The Enclosure walls of 1793 were required to be 6 feet high (1.82m) (Over Close 255 2a and 3a, and 2b and 3b for example) yet this specification does not appear to have been met. Wall heights or height variations therefore cannot be used on their own to establish a chronology.

Sinuosity

The same idea of using a population standard deviation for sinuosity measurements can be used to characterize departures from linearity in plan view. Small-scale sinuosity is here defined as irregular sideways deviations from linearity observable every metre. It is proposed that the extent of these minor deviations from what appears to be a section with straight construction line is related to age. A plan view such as shown in Figure 3 is what is being considered and amenable to characterization by the method proposed. We are not looking at a wall as it was several hundred years ago, but what it has become after this time.

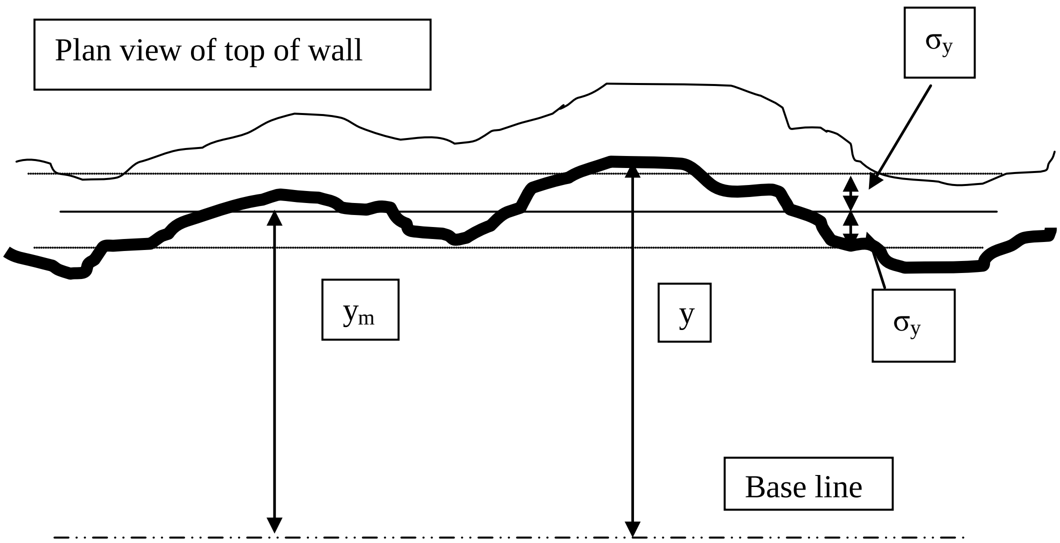


Fig 3 Wall Sinuosity

Solifluction and ground creep can result in wall movement if it is not built on solid rock. Mitchell records comments from farmers that frozen ground may thaw more quickly on one side of a wall due to orientation and sunlight and cause a wall to ‘walk’. Movement causes slumping and bellying, worsened by weather and animal damage (sheep, deer, and rabbits have all been seen climbing walls). Moorhouse remarks that although there is evidence that walls were pulled down and rebuilt many times over centuries, what is likely to survive is the foundation course. It is usually very difficult to follow the base stones so the sinuosity near the top of the wall was measured instead. Measurements for eight different wall samples (each of 50 measurements at 0.5m intervals) at the base, wherever the base stones were well exposed, and near the top show that the sinuosity values near the top of the wall closely mirror those at the base and are statistically indistinguishable.[9]

Deliberate building in a sinuous manner is doubted since sharp curvature contributes to weakness. It seems unlikely that builders would curve sharply around a tree or large obstacle; tree roots lead to wall collapse. Dry-stone walls exhibit some plasticity or flexibility meaning that severe deformations can occur before collapse; mortaring of capstones or the wall stones prevents movement to alleviate stresses and allows earlier collapse. Repair of gaps to restore height of decayed walls is common whereas repair to reduce sinuosity is possible but less likely. During a repair the base stones may only be moved closer when the wall has slumped and the base has spread, according to a modern waller (Mr G. Walker).[10]

A nominally straight section of a wall is ideally required if it is to be well characterized. Unfortunately medieval fields are rarely neatly rectangular with long straight walls. Old walls tend to take a wavering course and take some account of the lie of the land. However, Winchester notes that 'an artificially straight boundary was agreed in 1256' (between Windermere and Staveley manors). The Saxton map of Ingleborough (1603) shows long straight boundaries to resolve transgressions. It should not therefore be assumed that all straight walls are of the 18th-century enclosure period or later. There is only one possible reversed s-shaped (aratral) Langcliffe Townfield wall (Pike 124). As Rackham suggests, piecemeal irregular enclosure seems to have taken place, possibly by small crofters to protect their land and to preserve benefits of the manure they were able to save.[11]

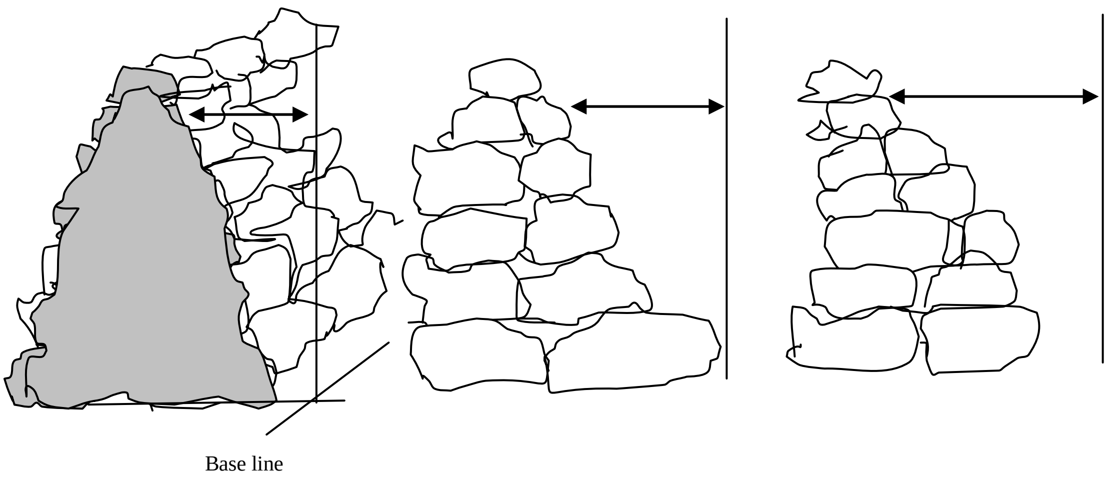


Fig 4 Collapsing walls

Measurement of sinuosity

A straight base line was set up using a 25m taut tape positioned nowhere more than about 1.5m from any part of the top of a wall to be measured and reckoned to be parallel to the building line (Figures 4 and 5).

The normal (i.e. at right angles) distances 'y' from the base line, measured to nearest 5cm, to the face at the top of the wall (just below capstones) at 1m intervals were recorded using a marked rod held horizontally with the eye set vertically over the base line.

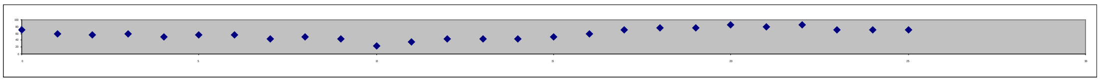


Fig. 5 Sinuous deviations with same scale on both axes

The use of a plumb line or a laser distance-measuring device proved awkward and slow and no more accurate. The wall section to be measured should not have any sharp bends or strong curvature and a fixed sample length is desirable for comparative purposes. Setting ranging poles no more than about 1m away from a wall and fully visible over 25m was helpful in defining a suitably straight section.

The results are dependent on the chosen scale of measurement intervals of 1m and the proposed sample length of 25m; these seem to be sensible choices but represent a balance between finding a sufficient straight length and an interval of the same order as the small-scale sinuosity. Test calculations for Langcliffe Scar (261 1a) data at 0.5m, 1.0m, 1.5m, 2m, 3m and 4m intervals showed that sinuosity values were insensitive to starting points 0.5m apart only for intervals up to 1.5m. One should aim to have multiple small deviations, randomly plus and minus, from the mean distance y_m away from the base line. Some walls show large scale sinuosity with local curvature on a scale of many metres, which is not the characteristic of interest here. The whole length of a field wall should be measured in as many 25m lengths as possible to obtain a reliable value of sinuosity σ_y. Both sides of a wall should be measured wherever possible.

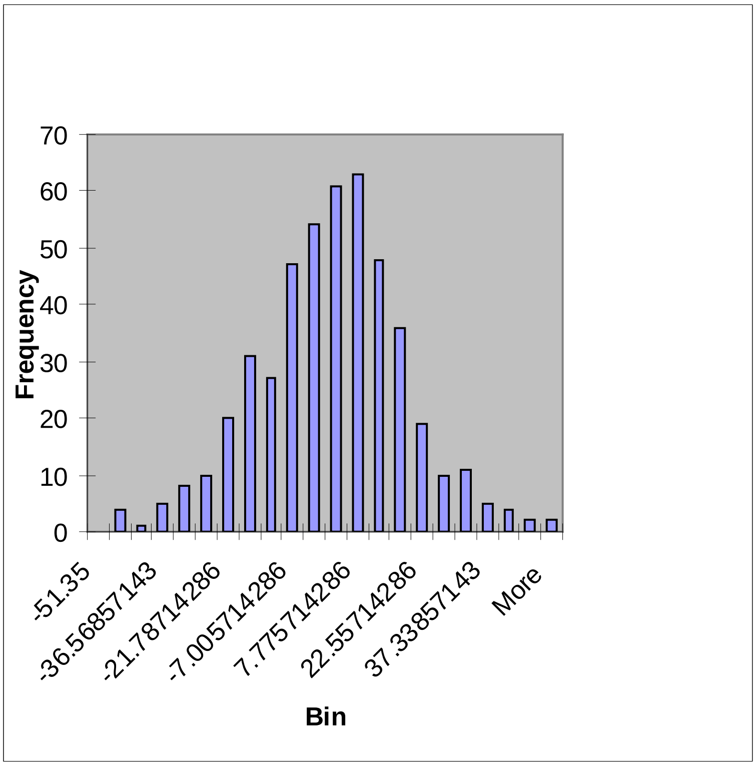


Fig. 6 Frequency bar chart

Distribution functions and statistical validation of sinuosity

Combined lists of (y-y_m) values for multiple samples of 25m put into an MS Excel spreadsheet are are used to calculate population standard deviation σ_y and are plotted as a frequency bar chart (Fig 6). It can then be tested if the shape can be fitted by the Normal distribution function for random processes or if some other function is more suitable. This allows setting of confidence limits and calculation of errors. (Figure 7).

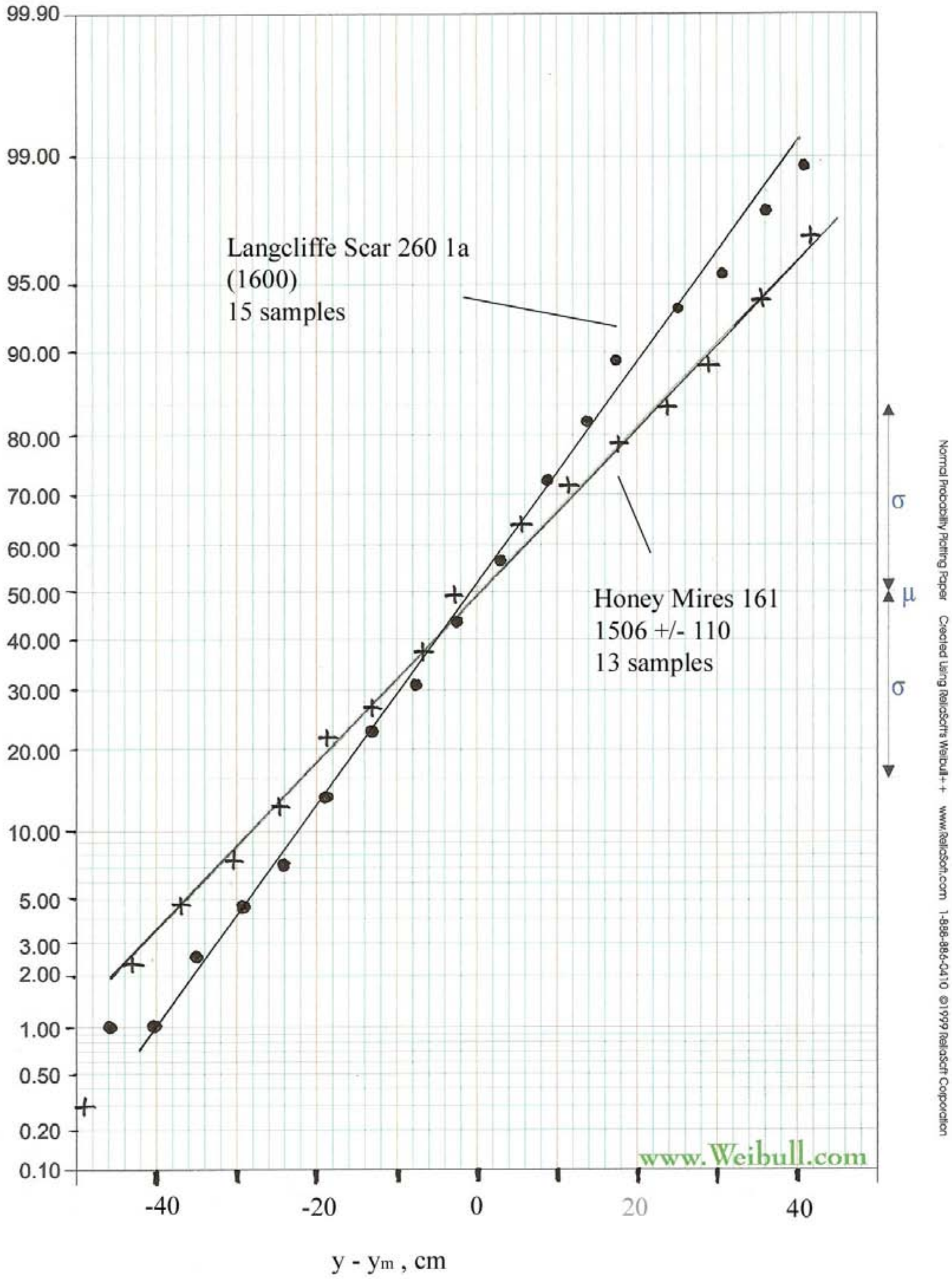


Figure 7 Probability Plot

Various bell-shaped theoretical functions exist so a visual inspection of a bar chart is insufficient to prove that the distribution is Normal. A test is easily made with probability graph paper, obtainable for example from *www.weibull.com/GPaper/*, which uses a vertical axis calculated to make the cumulative Normal distribution equation give a straight line plot (Figure 7).

The cumulative probability distribution values are provided in an MS Excel spreadsheet (Tools, Data Analysis, Histogram). Virtually all the data obtained in this project lie close to a straight line between 2.5% and 97.5% probability. The value of σ_y measured from the slope of the probability plot over a range of $4\sigma_y$ diverges much less than 0.5cm from that calculated using all the data, reflecting the influence of occasional extreme measurements of y. Deviations from the mean point of $y=y_m$, 50% probability are usually less than 2cm. Other distribution functions were tried without success. Further notes on sinuosity modelling are made in Appendix 2.

Known wall building dates

The building dates for a set of walls are now needed to obtain a correlation of wall characteristics with age.

In 1591 about 1000 customary acres of the high pasture land were sold to trustees and existing tenants. This pasture land can be identified with the help of the Enclosure and Tithe maps knowing that 1 customary acre = 1.62 Statute acre (known from later maps with customary and Statute acres inscribed). Part of the land was then sold on as '152 acres one rod, twenty poles' which can be identified most probably as Daw Haw, Cow Pasture and and Over Close (originally called Cowside Close) Tithe numbers 255, 256, 268, 277.[12] The containing walls should therefore be 400 years old or slightly more. In 1600 Henry Sommerscales bought the unenclosed Langcliffe Moor, 300 (customary) acres excepting 50 (customary) acres next to the Ewe Close.[13] This land can be identified as Tithe numbers 260 to 267 totalling near 300 customary acres with Langcliffe Scar 261 being of 50 customary acres. The surrounding walls were presumably in existence marking out the 50 acres in 1600 or a little earlier. The wall of Langcliffe Scar 261 has a rounded corner where it meets Langcliffe Scar 260. A deed of 1633 refers to 'Langcliffe Moor now inclosed called Scar Close'.[14]

A land conveyance of 1707 notes that William Stackhouse has transferred a parcel taken off ground called the Intack at Winskill to Richard Clapham. After walling this was to provide a way leading from Richard Clapham's ground called the Intack to his ground called Goasker. It is thought that this refers to Little Intack 249 at Winskill.[15]

A map of Settle Banks of 1756 shows enclosure walls. The wall going from the east end of Carts Coppy 188 south towards Stockdale was measured up to the point of the wall moving sharply downhill which has recently been rebuilt.

The Langcliffe Enclosure Act map of 1789 shows the walls to be built on the high grazing lands of Cow Close, Over Close, Langcliffe Scar, Daw Haw, Winskill Stones, Cowside and Gorbeck. Only one other wall seems to have been built there by 1841 (Tithe map). The Enclosure process required owners to build the specified walls by 1794.

In 1845 Anthony Stackhouse, Henry Dawson and Frederic Dawson agreed on a land transfer at Brown Bank (in Stainforth parish near Stainforth Foss) in which Stackhouse was required to build a short wall to separate the land.[16]

A map of the lands belonging to G. A. Paley of Langcliffe was made in 1920 when all the holdings were sold. The wall delineating Chamberlain's Overclose is not found on the Tithe maps but is seen on the OS map of 1898.[17]

A large intake on Winskill Stones (not marked on the Tithe map and not on 1st Edition OS 1847) was probably made about 1860 when farming was enjoying profitable times. It appears on the 1898 OS map.

The railway built around 1870 has walls along its length, with straight sections accessible in Langcliffe parish.

A wall was constructed of Silurian flagstones in 2007 at Dry Rigg Quarry. In 2008 a new wall was built around the Langcliffe Place caravan site. A limestone wall was constructed in 2011 by the main road south of Selside for the Settle Loop bridleway.[18]

The friction relationship

The possible relationship between forces trying to move the footings and forces resisting such movement is now considered prior to suggesting a correlating equation for age as a function of sinuosity and wall weight.

Horizontal forces causing ground movement depend on many physical variables but water is likely to be a major factor. Expansion of water as it turns to ice can easily exert pressure of 3 tonne/cm^2 depending on how it is constrained and applied so the forces at work seem adequate to move a wall. Lateral earth pressure due to different soil levels each side of a wall is likely to be much smaller but still sufficient to move a wall. Forces act occasionally for short time periods, moving walls a little at a time. A series of equilibrium states is experienced.

The resisting horizontal sliding frictional force at the base level, F_s , is proportional to the weight of the wall, W, which is a downward force. The coefficient of proportionality μ_s is known as the coefficient of friction (values between 0 and 1 for sliding friction).

$$F_s = \mu_s W \qquad (1a)$$

In addition there will be a resisting force dependent on the structure of the wall; there is lateral bonding by friction between stones in the line of the wall which is akin to sideways bending resistance in a solid beam which counteracts deflection except that the effect is not elastic because the stones move out of position. Through-stones will increase internal frictional resisting forces and so reduced sinuosity should be expected compared to a wall without through-stones of the same age. Similarly, irregular blocky stones may offer less resistance to wall deformation than flaggy or quarried stones. This internal resistance is found by experiment with layers of wood blocks of different surface roughness to increase with number of layers, hence weight. The force F_i required to overcome this internal resistance is therefore expressed as

$$F_i = \mu_i W \qquad (1b)$$

and the total force is

$$F = \mu_s W + \mu_i W = \mu W \qquad (1c)$$

where μ is a composite coefficient dependent on the nature of construction and shape of stones. It is proposed to include μ W in a correlation to determine the age of a wall.

For walls built across a slope the Equation (1c) becomes

$$F = \mu W \cos\theta \qquad (1d)$$

where θ is the angle of the slope to the horizontal. For a 30^o slope the resisting force affecting movement is reduced by a factor of 1.155. From a practical point of view one cannot measure slope angles for all samples but this helps to explain and quantify some of the variation of sinuosity for walls of the same age.

Correlation of sinuosity with age

It is postulated that wall age is proportional to the resisting force F and to distance moved, characterized by σ_y , in the time elapsed. Force multiplied by distance corresponds to the amount of work done to move the wall.

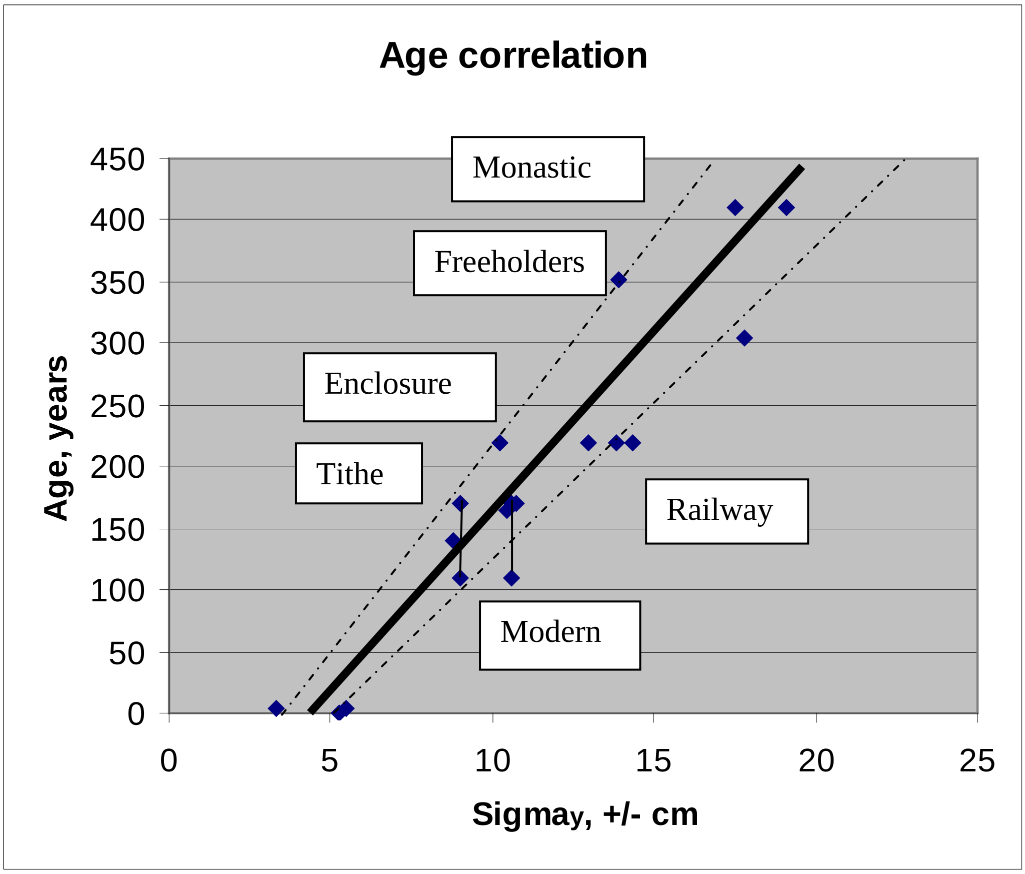


Fig. 8 Age correlation

Rather than using the absolute weight of a wall, a 'standard size wall', being double-sided narrow-topped, 80cm wide at the base, 40cm at the top, and 1.6m high is used to calculate a relative weight factor, w. The cross-sectional area of a wall is proportional to weight and appropriate weight ratios can be calculated. This allows note to be taken of how different a wall is relative to the standard. For a given value of σ_y heavier walls are likely to be older than lighter ones because heavier walls resist movement more. The weight must depend on the internal void space, probably about 20% in Langcliffe walls, but for others built of close-fitting slabby stones voidage will be nearer 10%. Stone density will also vary according to type. These latter factors cannot easily be accounted for but will be a source of variation in wall characteristics.

The combined data from Table 2 which give satisfactory Normal distributions show a rational relationship between sinuosity, relative wall weight factor, w, and age (Figure 8). All measurements were made by one person (MJS). We propose Equation (2) to express the data for walls up to about 250 years old and the statistical best fit line was found by linear regression (using *statpages.org/nonlin.html*) to be for age, A, in years,

$$A = 29\, w\, (\sigma_y - 4) \quad \text{+/-46 years for 68\% confidence limits} \qquad (2)$$

($0.5 < w < 1.0$ and $3 < \sigma_y < 19$ approximately, σ_y in cm)

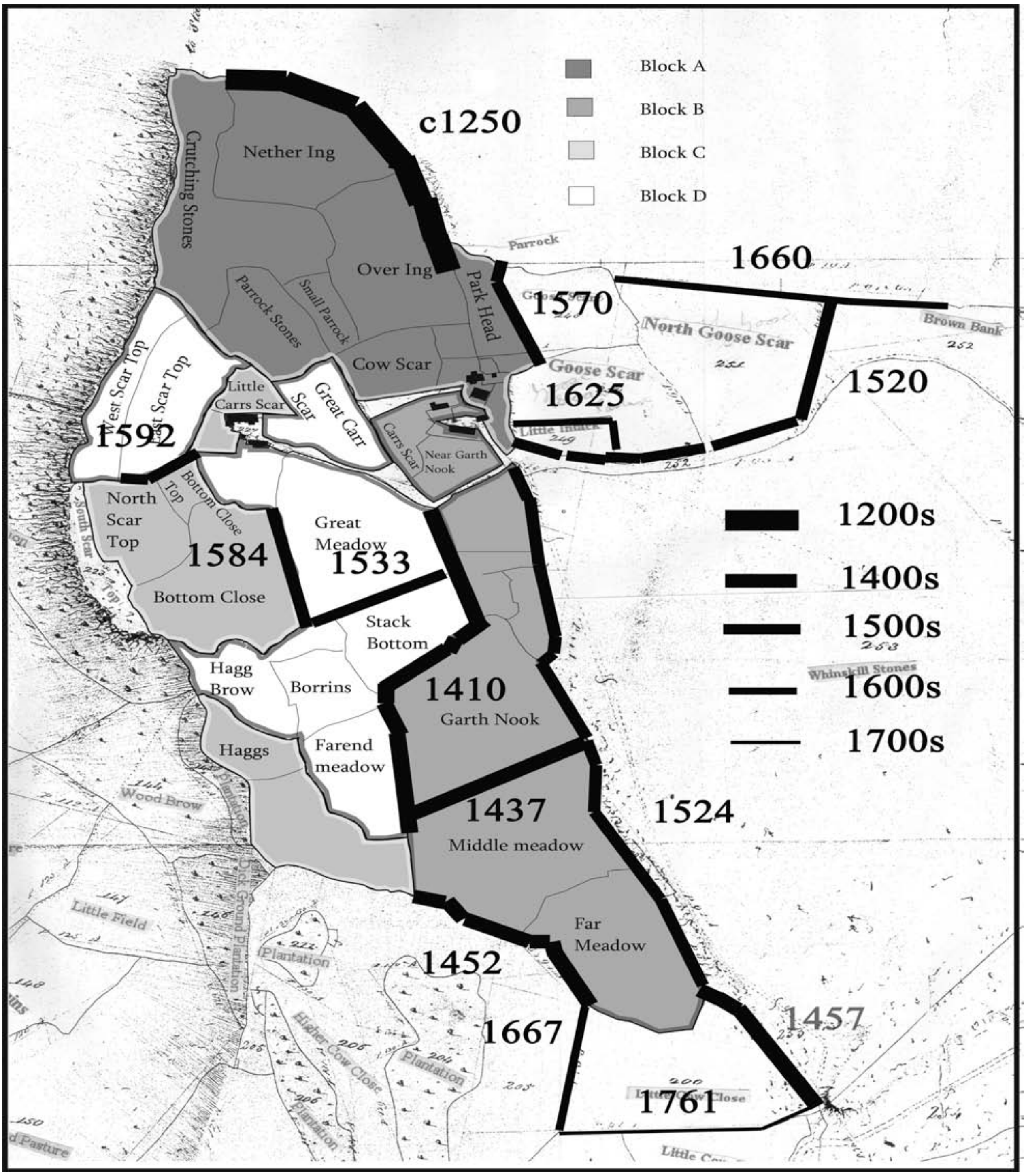
with root mean square error, i.e. an average error, of +/- 46 years and correlation coefficient R = 0.92, indicating a reasonably high degree of goodness of fit. The equation serves as the trend line for older walls. The intercept value 4cm at zero age is the typical minimum sinuosity of a new dry-stone wall, with variation of the distances each side of the the mean building line of about 5 to 10cm, reflecting the irregularity of the position and surface of stones.

The random experimental errors in y and w lead to a relative standard error of age (e_A/A) which can be estimated well enough for $\sigma_y >> 4$ from

$$(e_A/A)^2 = (e_w / w)^2 + (e_y / \sigma_y)^2 \qquad (3)$$

A simple approximation is about +/-15% on age since both (e_w/w) and (e_y/σ_y) are about 0.1. These errors are in accord with the correlation graph data. It is clear that much but not all of the spread of sinuosities at a given age is accounted for by measurement errors and the remainder is due to characteristics of the wall and the ground on which it stands. A subjective estimate of age taking the experimental error and these other physical factors into account can then be made. (See Appendix 3).

Two root mean square errors on age each side of the main line on Figure 8 encompass 95% of the data; one root mean square error each side covers 68% of the data. These are the 95% and 68% confidence intervals. It is considered that the upper confidence limit lines are more appropriate for well-repaired walls and the lower confidence limit lines for walls in poor condition or on soft foundations or across a slope. The value of μ will affect the coefficient of 29 which will vary with wall construction and stone shape. There is no obvious change in building style (i.e. with coursed through-stones) for Enclosure walls of 1793 or after this date which could affect the correlation. Walls built on solid rock not subject to soil pressure are unlikely to be characterized by the equation.



Extension of the graph to greater ages is uncertain in the absence of data but linear extrapolation is currently advocated. A wall might collapse before sinuosity reaches say 30cm. However, the line securely based on post-1756 dates (i.e. for ages from near zero to 255 years old) passes through data for older walls dated from documentary sources suggesting that these older walls were constructed near the dates assumed.

Individual extreme deviations from average values y_m of the order of +/-40cm are found for old walls. If a wall 400 years old suffers lateral movement of +/- 40cm an average movement of 1.0mm per year is indicated. The slope for Equation (2) of (1/29w) when w=1 is equivalent to about 0.3mm/year and is a measure of creep rate. In comparison solifluction (freeze/thaw) rates of 5 to 150mm per year have been reported and soil creep rates in low meadows in mountain country have been reported as 2 to 3mm per year. There is therefore nothing extreme in these values of wall movement. It is likely that most movement occurs intermittently in occasional periods of extreme weather.[19]

Application to other walls of known age to test predicted estimates

1. Chamberlain's Over Close 259 (1b) (54^o 05' 22.11" N 2^o 14'14.02"W; Google Earth reference)
This appears as one close on the Tithe map of 1841 but a good wall across it appears on the Paley estate map of 1920. This wall has sinuosity of 9.7cm, 12 samples, w = 0.96. These data give build date 1852 +/- 36 years with 68% confidence limits.

2. Little Cow Close 200 (2a) (54^{o}05' 20.47"N 2^{o}15'23.52"W)
This wall is an Enclosure wall (1793) and for sinuosity of 12.9cm, w = 0.87, it has a predicted build date of 1786 +/-42 with 68% confidence limits.

3. East and West Scar Top 229 and 230 (54^{o}05'35.76"N 2^{o}16'01.10"W)
A settlement of 1607 for the marriage of Thomas Foster refers to a short wall separating West and East Scar Top at Winskill yet to be built; this has been lost to the quarry below. The wall between these two fields and North Scar Top and Bottom Close Top should pre-date this separation (sinuosity 19.0cm, 4 samples, w = 0.88, 1628 +/-57 for 68% confidence limits).[20]

Walls with slabby gritstone

The Edge, Green Gate Lane, Long Preston (54^{o}01'43.30"N 2^{o}15'30.26"W)
This long straight field wall is considered to be an Enclosure period wall in Long Preston (Award made in 1815). It is built of slabby close-fitting gritstone and has regular rows of throughs. The sinuosity is 8.7cm, 6 samples, w=1.06, estimated build date 1867+/- 36 for 68% confidence limits. These data place the wall on the upper 68% confidence limit line of the correlation graph which suggests that the improved strength of the wall built with throughs is in line with expectations, having a higher friction coefficient hence a greater coefficient than 29 (nearer 40).

Ravenstonedale, near Kirkby Stephen (54^{o}26'28.67"N 2^{o}25'01.60"W)
We have a map of 1560/1 and the walls reach nearly 3m in places with a base width of about 1.2m. The construction of this high status park wall is very even with closely fitting slabs of limestone or sandstone with very little free space between the flat surfaces. It is found that for the highest section (average height 2.4m, maximum 2.95m, less than 100m long, w = 2.36) the sinuosity is remarkably small, i.e. 5.6, 7.5 and 8.9cm for 3 samples only and a very poor bar chart. Again, a higher coefficient than 29 is suggested. A value of 40 as for The Edge noted above gives a nearer estimate of age.[21]

Application of the method to walls of unknown age

The data allow construction of a map of Winskill (Table 3 and Figure 9) and in due course of the Langcliffe Townfields to show the possible development of the fields. Many of the existing fields at Winskill are named as closes in 1591 and are identifiable so the wall lines must have existed before then. The border between properties bought by Thomas Foster (younger) and Richard Foster (younger) existing in 1591 has been established using field names and field areas. The estimated build date range is 1388 +/- 76 for 68% confidence limits.[22]

For walls at Winskill bounding Little Intack, Goose Scar and North Goose Scar along the side of the lane to Stainforth Foss, and Great Field, Rake Scar and Far Meadow bounding the lane to the Langcliffe - Cowside road, it is considered that these are associated with Richard Foster's farm in 1591 at the time of the sale of Langcliffe Manor by Nicholas Darcy to the several Foster families of Winskill. The estimated build dates are near 1530 +/- 65 for 68 % confidence limits. The two closes Nether Ing and Over Ing are noted in the 1591 sale document for Winskill and Cowside and are here estimated to be built in the 15th century. [23]

The substantial manorial boundary wall of Nether Ing and Over Ing (with Stainforth) is considered stylistically to be medieval, being double-sided wide-topped, with near vertical sides, in part with protruding flat capstones, and much heavier than walls used to construct the age correlation. The Nether Ing/Over Ing (238, 1a; 237, 1a) wall has an average height of 1.79m so is considered to be about 1.6 times heavier than the A-shaped standard wall (w=1.6). The date is about 1218 +/- 88 for 68% confidence limits, strongly supporting the suggestion that the wall is medieval in origin.

The wall of Over Close 255 at the edge of the high pastures (wall 5b, a boundary of the 1000 customary acres mentioned in the sale document of 1591) is a narrow top type but 1.74m high on average, sinuosity 19.65cm, 4 samples. The weight factor of w = 1.10 leads to an estimate of 1512 +/- 66 years for 68% confidence limits.

Looking further afield, an east-west curving boundary lies between Over Pasture and Sulber near South House (Selside) in Upper Ribblesdale (54^{o}09'34.70"N 2^{o}20'03.74"W). The current wall shows extensive sinuosity (Figure 10) for no obviously good reason. Most of the wall is double-sided narrow-top but a stretch of wide-top with overhanging capstones is present along with modern sections. The wall has been repaired in a central long stretch and in other short sections as is generally seen in the well-set capstones at 45^{o} and as confirmed by the farmer. The values of the sinuosity for each 25m sample appear to agree with this observation, falling roughly into two separated groups, 9.2 to 16.3cm and 18.6 to 34.2cm (Figure 11). The overall wall height on average is 1.47m and is approximately 80cm base and 40cm top width on rough pasture ground. The data give a bar chart which is almost bimodal and a probability plot which is straight only between 15 and 95%. For the group of 15 high values of σ_y the compounded value is 25.9cm, w=0.92, and a date of 1427+/-75 for 68% confidence limits. For the group of 17 low values the compounded value is 12.7cm, w=0.92, build date 1779+/-44. The overall data give 18.0cm, w=0.92, 1637+/-50. These results suggest that the wall follows the line of an ancient boundary.

Fig 10 Over Pasture zig zag wall.

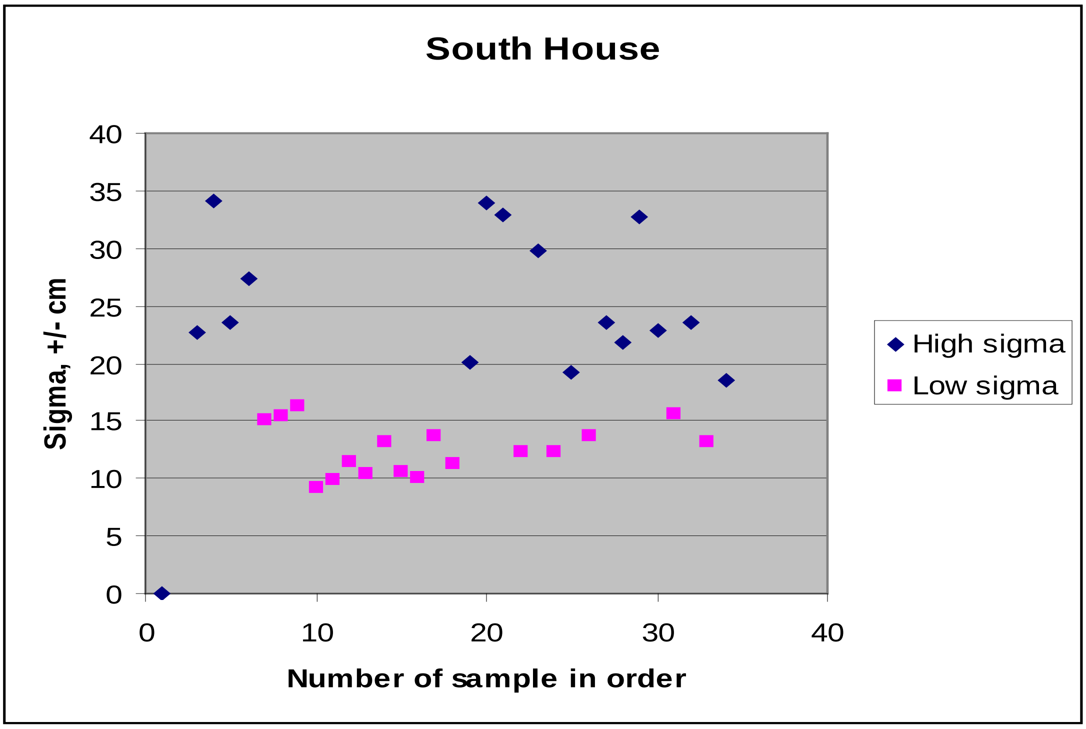


Fig. 11 South House data

The wall in Watlowes dry valley above Malham Cove is considered to be c. 1250s in origin, separating the lands of Fountains Abbey and Bolton Priory (54°04'25.56"N 2°09'31.04"W).[24] It lies on flat dry ground. The name Watlowes may derive from Old Scandinavian *vatnlauss* – waterless.[25] The wall sections WL/01/01 and WL/01/02 have recently been rebuilt but yield dates of 1572 and 1645 (σ_y 16.3cm and 14.4cm, 15 and 10 samples respectively) having been corrected for weight factors of 1.23 and 1.22 based on dimensions determined by Lord et al..[26] These sections are continued to the south to the edge of the cove by a wall outside the National Trust boundary which is unrepaired; this section of about 100m (8 samples, σ_y 19.9cm, w 1.51) gives a date of 1315+/-82 for 68% confidence limits. Wall heights were measured both sides, as well as bottom width and top width, 92 measurements for each (every 1m, neglecting a few broken sections). The height is essentially the same both sides at 166cm (standard deviation 13cm), the average bottom width is 120cm (s.d.17cm), top width 56cm (s.d.11cm).

A map of disputed land on Ingleborough drawn by Christopher Saxton in 1603 shows walls running near southwards from The Lord's Seat on Simon's Fell. One of the walls (54^o 09' 41.77"N 2^o22'20.89"W) is in good condition with an average height of 1.27m and a sinuosity of 12.9cm, giving a build date around 1800. The second wall (54^o09'48.78"N 2^o22'00.75"W) is quite different in shape and sits on boggy ground. A rough value of w is 0.8 and sinuosity is about 20cm for 10 samples which gives a build date of 1640+/-57.[27]

Conclusions

The standard deviation of wall height can be used as a measure of variation in wall height but with no correlation with wall age. The heights agree with an original specification of seven quarter yards (1.60m) for all the walls surveyed but seem not to agree with the 6 feet (1.83m) specified in the Enclosure Award.

Small scale sinuosity of a wall is a feature amenable to mathematical modelling. The theoretical Normal distribution of measurements of deviations of distance from the mean build line fits the data well. The population standard deviation from linearity (here called sinuosity, σ_y) of multiple 25m sections correlates rationally with age when combined with relative wall weight, w. A proposed equation based on data for walls of up to certainly 250 years old and possibly more is

$$\text{Age} = 29\, w\, (\sigma_y - 4) \quad \text{years}$$

(for $0.5 < w < 1.0$ and $3 < \sigma_y < 19$ approximately, σ_y in cm)

The experimental error in age estimated from this equation is about +/-15%. Final judgement of age can then be made subject to physical factors.

The weight of a wall is a factor in resisting lateral movement indicated by the sinuosity. For early heavy walls we find agreement of calculated age estimates with those made on grounds of style of construction. However, a higher value than 29 should be used for walls built with slabby stones closely fitting to each other when the friction between stones is expected to be much higher than for walls made of rough irregularly sized stones. The equation should not be applied to walls built on bedrock and not subject to soil pressure.

It seems remarkable that despite all the different mechanisms involved in wall decay and partial rebuilding and all the possible errors, and non-uniform decay rate, nevertheless a simple measurement of sinuosity together with relative wall weights results in a useful relationship with age. The high correlation coefficient cannot be lightly dismissed and so age estimates made as proposed must carry more weight than those made on subjective or stylistic grounds alone.

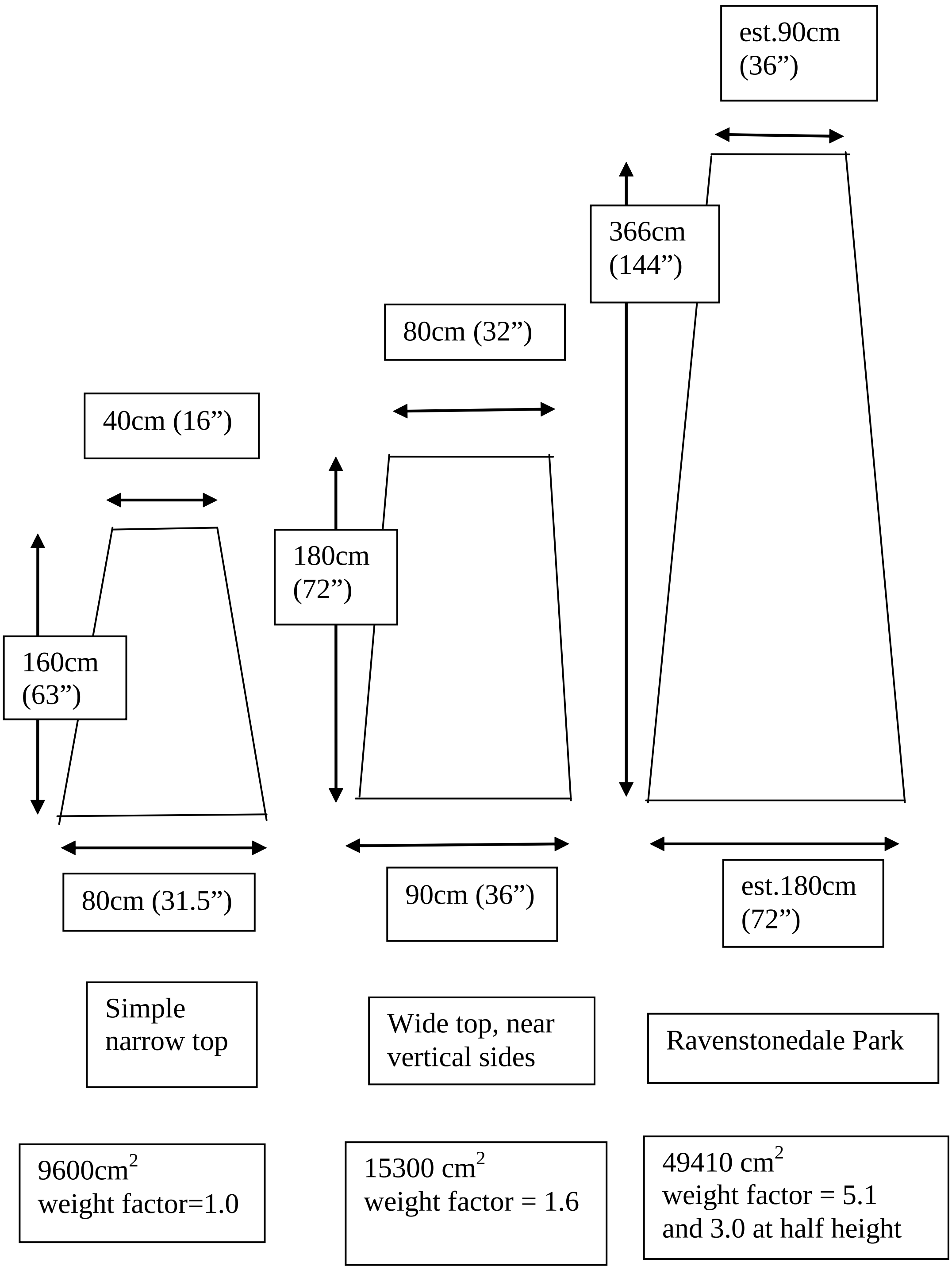


Fig 12.Wall Shapes

The methodology described is therefore worthy of further consideration. An understanding of the underlying statistics is not necessary but the procedure should not be changed from that proposed to avoid drawing unwarranted conclusions.

Finally there is a need to measure other walls which are known to be 400 years old or more to reinforce the type of correlation proposed. The work continues with Langcliffe townfield walls of unknown age to add to the more than 14,000 sinuosity and height measurements made so far.

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APPENDIX 1

The Normal distribution function

The Normal (or Gaussian) Distribution concerns a set of randomly varying measurements around an average (the mean) value. The Normal Distribution function shape for frequency f of N wall height values H with arithmetic average value H_m and population standard deviation σ_h is given by the equation

$$f = (1/\sigma_h\sqrt{[2\pi]}) \exp [- (H-H_m)^2/2\, \sigma_h^2] \qquad \text{(A1.1)}$$

The standard deviation for the population is easily calculated from a list of H values using the STDEV function in MS Excel or a scientific calculator.

$$\sigma_h = [\, \Sigma\, (H-H_m)^2/(N-1)\,]^{\,0.5} \qquad \text{(A1.2)}$$

Standard deviation is a valid measure of variability regardless of the distribution shape but if the data are Normally distributed about a peak frequency height value, we would expect 68% of the measurements to lie within a range of the mean value plus or minus one standard deviation, σ_h, and 95% to lie within plus or minus two standard deviations. In practice the numbers of H values within specified increments of height are used as frequencies and for comparison with data Equation (A1.1) is multiplied by the number of measurements N and the increment size into which the variable H range is divided (0.1m in our case). In most cases there is good agreement of the theoretical Normal Distribution and the data. The same equations are used for $(y - y_m)$ values to give sinuosity σ_y.

APPENDIX 2

Sinuosity modelling

A polynomial equation might be used to fit the graph of distance from baseline (y) against distance along the sample of wall (x) with fitting parameters, a, b, c etc., e.g.

$$y = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6 \ldots\ldots. \qquad \text{(A2.1)}$$

Non-linear curve fitting software is available at *www//statpages.org/nonlin.html*. The data were fitted with equations of increasing order to find best fit. As a wall suffers greater sinuosity, the order of the fitting equation (highest power of x) might increase and be expected to be a function of age. However, it was found that the order of a polynomial is not sufficiently discriminatory for current purposes.

A sinuosity index is used to describe rivers in which case the actual sinuous length is divided by the shortest path between two points. Rivers meander markedly and the index can have values much larger than 1.0. The index is the same in principle as used in fractal dimension relationships. The index method is found to be unsuitable for description of wall sinuosity since the index is so close to 1.0.

Simple averaging of standard deviations for each 25m sample can be done by taking the square root of the average of standard deviations squared but may only be done when the number of samples is large.

Additional measurements from a different starting point will invalidate the data because the scale of sinuosity measured then becomes more detailed (as in fractal analysis). This is tantamount to measuring the fine structure of the wall face, not a variation per 1m.

APPENDIX 3

Errors in age estimation

There is a subjective measurement error of up to about 15cm in wall height so $e_w \approx 15/160$. A tenfold repeat of measurement of σ_y for a fixed baseline on one wall section (Astall 134, σ_y 14.5cm, s.d. 0.3cm) showed that measurement error due to rounding to the nearest 5cm was near 0.5cm. It can be shown mathematically that as the baseline diverges from being parallel with a supposed building line an increase in sinuosity is incurred with a minimum value when these lines are parallel. The Solver routine in Excel is easily used to find this minimum sinuosity. The difference between the measured sinuosity and minimum values (assumed valid for parallel baselines) is about 0.5cm when σ_y is 5cm and 2.0cm at 20cm, the majority being less than 1.5cm. These values are associated with a divergence of one end of the baseline usually up to about 15cm from where it perhaps should be. A mathematical check showed that an arbitrary divergence of +/-30cm forced the probability plot about 15cm away from the mean point of (0,50%) so this is a good indicator of a suspect measurement; the sinuosity is however is not very sensitive to this source of error. A total approximate experimental error e_y of +/-2.0cm is therefore cautiously adopted.

TABLE 1 Wall heights at Winskill and the high pastures

Field (Tithe name)	Wall	Current average height, m	Weight factor, w	Height Population Standard deviation, σ_h, cm	Sinuosity, σ_y ,cm	Position ref. **
Clay Pitts 192/189	1a	1.36	0.85	10	17.4	54.04.52.82N 2.15.13.16W
Clay Pitts 192/189	2a	1.28	0.80	16	21.4	54.04.45.48N 2.15.08.35W
Little Clay Pitts 193	1a	0.82	0.51	29		54.04.51.25N 2.15.18.52W
Little Cow Close 200	2a, 2b	1.40	0.87	13	12.9	54.05.20.27N 2.15.24.23W
Far Meadow 201	1b	1.54	0.96	11		54.05.26.33N 2.15.28.41W
Middle Meadow 202	1b	1.46	0.91	14	25.5	54.05.29.74N 2.15.34.77W
Haggs Brow 214	1a	1.39	0.87	22		54.05.30.06N 2.15.56.16W
"	2a	1.88	1.18	30		54.05.31.35N 2.15.54.32W
"	3a	1.31	0.82	21		54.05.32.09N 2.15.51.89W
"	4a	1.45	0.91	21		54.05.31.66N 2.15.50.97
Little Stack Bottom 215	1a	1.67	1.04	14	28.0	54.05.31.49N 2.15.48.14W
"	2a	1.52	0.95	10	"	54.05.31.01N 2.15.46.68W
"	3a	1.44	0.90	13	"	54.05.29.95N 2.15.47.91W
"	4a	1.50	0.94	10	"	54.05.29.67N 2.15.50.03W
"	5a	1.42	0.89	9	"	54.05.31.80N 2.15.50.60W
Far End Meadow 216	1a	1.62	1.01	7	28.5	54.05.29.40N 2.15.44.70W
	2a	1.42	0.89	12		54.05.26.77N 2.15.43.52W
	3a	1.14	0.71	22		54.05.27.23N 2.15.47.09W
	4a	1.36	0.85	15		54.05.30.00N 2.15.47.77W
Garth Nook 217	1b	1.56	0.98	11		54.05.32.94N 2.15.38.73W

Rake Scar 218	1b	1.50	0.94	23		54.05.35.72N 2.15.41.06W
Stack Bottom 220	1a	1.63	1.02	9	21.5	54.05.35.17N 2.15.44.86W
“	2a	1.67	1.04	11	“	54.05.32.89N 2.15.45.02W
“	3a	1.47	0.92	15		54.05.31.89N 2.15.48.88W
“	4a	1.12	0.70	13		54.05.34.58N 2.15.48.40W
Bottom Close 222	4a, 4b	1.41	0.7	11	19.2	54.05.34.33N 2.15.53.40W
West and East Scar Top 229, 230	4a	1.41	0.88	19	19.0	54.05.35.57N 2.16.01.54W
Crutching Close 236	1a	1.51	0.94	24		54.05.43.66N 2.15.58.74W
Nether Ing 237	1a	1.74	1.09	16		54.05.48.96N 2.15.58.06W
Over Ing 238	1a	1.76	1.6 (0.80, 0.90)*	17	22.0	54.05.46.53N 2.15.53.74W
Little Intack 249	1a, 2a	1.51	0.94	8	17.8	54.05.42.27N 2.15.42.34W
Winskill Stones 253 intake	1b	1.36	0.85	8	10.6	54.05.41.22N 2.15.35.04 W
“	2b	1.38	0.86	10	“	54.05.40.54N 2.15.28.14W
Over Close 255	1a	1.32	0.83	14		54.05.10.35N 2.14.59.83W
“	1b	1.53	0.96	16		54.05.10.35N 2.14.59.83W
“	2a	1.36	0.85	13		54.05.14.88N 2.15.00.12W
“	2b	1.48	0.93	14		54.05.14.88N 2.15.00.12W
“	3a	1.34	0.84	24		54.05.21.15N 2.15.05.48W
“	3b	1.41	0.88	20		54.05.21.15N 2.15.05.48W
“	5b	1.74	1.10	26	19.7	54.05.14.92N 2.15.12.51W

a – inside field, b – outside field
* height (top width, bottom width)
**Google Earth Position references (degree.minute.second.decimal second)

TABLE 2 Sinuosity data used to construct age correlation graph

Field	**Wall Position ref.****	**Combined σ_y cm**	**Date**	**No. of samples of 25m**	**Source**	**Height, m**	**Weight factor, w**	**Height Population Standard deviation, σ_h, cm**
Langcliffe Scar 260	1a 54.05.01.16N 2.14.44.13W	16.7	1600	18	1600 sale	1.37	0.86	9.8
Langcliffe Scar 261 (other side of LS 260)	1a 54.05.01.16N 2.14.44.13W	19.1	1600	15	1600 sale	1.37	0.86	9.8
Carts Coppy 188	1b, 2b, 3b 54.04.38.15N 2.15.04.54W	13.9	1659	18	Sale deed	1.38	0.86	14.5
Little Intack 249	1a+2a +1b+2b 54.05.42.27N 2.15.42.34W	17.8	1707	10	Stackhouse/ Clapham deed	1.50	0.94	8.3
Settle Banks, Attermire	54.04.33.85N 2.14.56.90W	14.2	1756	10	Settle Banks Enclosure Map	1.42	0.89	12.2
Settle Banks, Blua 186	5b 54.04.23.10N 2.15.53.39W	11.5	1756	12	Settle Banks Enclosure Map	1.54	0.96	18.1
Winskill Stones Encl. 253	54.05.31.05N 2.15.12.91W	11.9	1793	16	Enclosure Act	1.47	0.92	15.8
Over Close 255	2a+3a 54.05.18.41N 2.15.03.01W	14.3	1793	8	Enclosure Act	1.30	0.85	18.5
Over Close Mdow 257	3a 54.05.19.56N 2.14.32.15W	13.0	1793	3	Enclosure Act	1.46	0.91	10.5
Over Close 256	1a 54.05.22.33N 2.14.49.25W	10.2	1793	8	Enclosure Act	1.38	0.86	10.7
Chamberlain's Over Close259, Far Over Close 238	2a 54.05.25.42N 2.14.22.38W	14.2	1793	13	Enclosure Act	1.48	0.93	14.3
Cow Close	1a	14.1	1793	24	Enclosure	1.40	0.88	14.2

197	54.05.03.81N 2.15.23.82W				Act			
Over Close Meadow 257	1a+2a 54.05.23.76N 2.14.35.01W	10.7	1841	6	Tithe map	1.59	0.99	12.2
Brown Bank (Stainforth)	1a 54.05.56.06N 2.15.25.35W	10.5	1845	3	Dawson Deed	1.35	0.84	11.3
Winskill Stones 253 (intake)	1b+2b 54.05.40.38N 2.15.33.57W	10.6	1840-1898	8	T. Lord	1.35	0.84	8.9
Chamberlains Over Close 259	1a 54.05.22.62N 2.14.14.04W	[9.0]	1841-1898	4	Paley map	1.54	0.96	5.7
Jacks Wood 118	54.05.13.86N 2.16.22.30W	8.8	1870	3	Railway	1.20	0.75	16.5
Roundgate 98	4a 54.04.58.55N 2.16.35.93W	10.0	1870	5	Railway	1.55	0.97	13.9
Dry Rigg (Horton)	54.07.06.86N 2.18.08.01W	3.4	2007	2	Quarry	1.0 (0.45/0.65)*	0.57	-
Roundgate 98 / Slapestones 91	1a + 2a 54.04.58.64N 2.16.41.35W	4.1	2008	6	Caravan site	1.29	0.80	3.9
Selside	54.10.02.67N 2.19.35.74W	5.2	2011	2	Bridleway	1.15	0.66	-

5044 measurements a – inside field, b – outside field
* height (top width, bottom width)
**Google Earth Position references (degree.minute.second.decimal second)

TABLE 3 Winskill age data

Field	**Wall Tithe no. and grid ref.**	**No. of 25m samples**	**Weight factor, w**	**Combined σ_y , cm**	**Estimated build year**
Border between Winskill Blocks Thos. Foster (younger) and Rich. Foster (younger). Both sides	Great Mdow 221, 2a; Stack Bottom 220, 1a, 2a; Far End Mdow 216 1a; Farmost Pasture 212 1a,Grt Field 219, 2a;GarthNook 217,2a;MiddleMdow 202 3a 32.85"N 45.03"W	20	1.0	25.5	1388 +/- 76 Walls bounding 4 fields so somewhat suspect but it should be an early boundary.
Lane border Little Intack, Goose Scar, North Goose Scar	249, 250, 251 both sides 42.78"N 36.10"W	11	0.95	21.5	1528 +/- 65
Lane border Great Field, Rake Scar, Garth Nook, Middle Mdow, Far Mdow	219, 218, 217, 202, 201 Both sides, all 1a 33.01"N 38.78"W	19	0.95	21.4	1532 +/- 65 Expected to be similar to lane set above.
Nether Ing Over Ing Park Head	237 1a 1b, 238 1a 1b, 247 1a 1b 49.01"N 58.25"W	11	1.6 *	21.1	1218 +/- 88 Possible medieval boundary
NetherIng, Crutching,	237 2a 3a, 236 3a, 4a,	10	0.94	26.5	1398 +/-77

OverIng	238 2a 46.78"N 58.88"W				
Little Cow Close, lane wall	200 1a and 1b 23.86"N 22.39"W	8	1.02	23.8	1426 +/- 73
Middle Meadow, GarthNook	202 2a, 217 4a 29.98"N 39.22"W	8	0.90	24.5	1476 +/- 71
Little Cow Close	200 2a + 2b other side 20.32"N 24.42"W	11	0.87	12.9	1786 +/- 42
Park Head 247, GooseScar 248	1a, 1a 44.65"N 48.44"W	6	0.94	19.8	1582 +/- 61
Bottom Close 222	4a 34.28"N 53.44"W	6	0.88	19.2	1622 +/-58
West/East Scar Top 229	4a 36.63"N 59.95"W	4	0.88	19.0	1629 +/- 57 Lord 2 deed. 1607
Middle Mdow, Far Mdow, Higher Cow Close	202, 201, 205 24.80"N 34.61"W	8	1.0	24.0	1432 +/- 73
Little Cow Close , Higher Cow Close	200 3a, 205 1a 21.08"N 30.74"W	8	0.98	16.3	1661 +/- 54
Grt Mdow, Stack Bottom	221 1a, 220 4a 34.53"N 48.40"W	7	0.87	21.1	1581 +/- 62
Little Intack	249 1a, 2a 42.06"N 43.34"W	10	0.94	17.8	1635 (1707 deed) +/- 56
Parish Boundary with Stainforth	47.49"N 39.39"W	15	0.99	16.5	1651 +/- 55

4212 measurements

Position References are 54^{o} 05'N and 2^{o} 15' in all cases; only the seconds and decimal seconds are indicated in the table.

* 85 cm top, 90 cm bottom

10th MAY 2014.