# Pleistocene and Flandrian Natural Rock Salt Subsidence at Arclid Green, Sandbach, Cheshire

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**Abstract.** This applied geological case study concerns the Quaternary geomorphological evolution of a small part of the lowland Cheshire characterised by 'equifinal subsidence landforms' resulting from the processes of rock salt dissolution and post Last Glacial Maximum glacial ice meltout. The context relates to environmental issues arising from the quarrying of Chelford Formation industrial 'silica sands'. Problems related to natural and human induced rock salt dissolution are reviewed. The respective roles of Triassic bedrock halites, collapsed strata, periglacial alluvial sands and multiple glaciation in determining the local stratigraphy and allied landforms are discussed. The morphology and fill of a post glacial subsidence area is examined. It is concluded that natural rock salt dissolution is the principal process influencing the superficial deposits and geomorphology of the study area and that this process has been active over hundreds of thousand years. The deposition and survival of thick silica sands and the glacigenic sediments beneath is probably due to halite dissolution.

In eastern Cheshire, a significant part of the lowland geomorphology is characterised by an excellent example of what, in 'General Systems Theory' jargon, would be termed 'equifinal behaviour' (Chorley, 1964), also known as polygenesis. Such behaviour in a geomorphological context envisages that different initial earth surface processes have resulted in similar morphological outcomes. Hence, equifinal landforms do not necessarily betray their primary causal origins, and geological observers should be vigilant when attempting to establish their genesis. Specifically, the Cheshire terrain is peppered by numerous hollows and troughs, including some which have yet to be fully integrated into the surface drainage network. Dependent upon the degree to which they have been infilled since their formation, this distinctive relief forms part of the classic Cheshire landscape of lakes (meres) and bogs (mires/mosses).

The key to identifying the significance of this particular group of landforms are two quite independent subsidence processes. These are :- (a) the decay of detached masses of buried glacial ice creating kettle holes in association with the deglaciation event which followed the LGM (Last Glacial Maximum) at c.20 ka BP, and (b) the dissolution, by circulating ground water, of saliferous beds within the Triassic bedrock succession. This latter, more-deep-seated, process induces collapse of the cover sediments and has been omnipresent process since preglacial times. However, in lowland Cheshire, a region of recent (Devensian) glaciation with a more than 90% blanket of superficial (drift) sediments, it is often far from easy to discriminate between depressions resulting from one or the other kind of subsidence, especially in the absence of exposures or any sub-surface data. Paradoxically, the field delineation of areas thought to be underlain by saliferous strata is frequently dependent upon accurate identification of landforms resulting from salt dissolution processes per se.

A further complicating factor is human induced salt subsidence exacerbated by historic shallow mining for salt and wild brine pumping, for example, Ward, (1887), Calvert (1915), Cooper (2002), Sherlock (1922), Wallwork (1956, 1960), Waltham (1989), and Waltham *et al* (2005). Following the near universal enforced abandonment of these extraction techniques in the 1970s, active subsidence arising directly from brine pumping is now much reduced. Anomalously the New Cheshire Salt Works at Wincham near Northwich was until recently able to continue wild brine pumping largely because of the extreme difficulty of attributing subsidence (and liability) to a specific site in an area of complex hydrogeology. Dormant future problems relating to old mines are not eradicated. An example of this relates to the central business district of Northwich. After initial spectacular collapses (Fig. 1), for over a century the hazard posed by catastrophic salt subsidence had been countered by constructing low rise buildings on adjustable frames (Waltham, 1989). Nevertheless, the conurbation core area remained in quasi-equilibrium as it was underlain by shallow C19th pillar and stall worked mines filled with saturated brine - a veritable ticking time bomb, as the pillars were degrading and the brine could drain at any future date. Understandably, this situation had discouraged redevelopment despite commercial pressures to do so. Under a government land stabilisation programme, a £28 million scheme that involved replacement of the brine with a grout consisting of mainly pulverised fuel ash was implemented between 2004 and 2007. This approach could only be justified where land values are high.

This contribution documents the issues relating to the recognition of subsidence landforms at Arclid Green (SJ 786612) just over 2 km east of the centre of Sandbach (Fig. 2). An investigation of the subsidence geomorphology contributed to the successful establishment and operation of a major silica sand


*Figure 1*. *Collapsed buildings in Northwich when wild brine pumping was at its zenith a hundred years ago.*

quarry, producing sands for foundry moulding and for making fibre glass insulation. As the new quarry expanded, it exposed pre-LGM sand sequences deformed by salt subsidence, features hitherto unique in Cheshire. Furthermore the distinctive stratigraphy provides constraint on the age of this process.

## Bedrock geology

Within the tectonically controlled Cheshire Basin rift system, is preserved a fill over 4.5 km of Permo-Triassic red bed sediments and locally Jurassic marine strata (Plant *et al.,* 1999). Below the aerially restricted Penarth Group, the uppermost part of this sequence constitutes the argillaceous red-bed Mercia Mudstone Group (formerly named the Keuper Marl) and this is now classified into seven formations (Wilson, 1993). The group is interpreted as the product of sedimentation in a playa and tidal flat environment, and includes major halite formations and anhydrite and gypsum-rich horizons. The regional key to unravelling the pattern of concealed subsurface crops of the Mercia Mudstone came with the boring in 1959-60 of a deep cored borehole at Wilkesley (SJ 629414). Some 16 km SSW of Crewe, this was located on a Lias outlier occupying the basin centre. Previously it was assumed that there was just a single major rock salt bed in Cheshire, but the Wilkesley cores revealed that two separate substantial saliferous units occur within the Mercia Mudstone. The estimated proven reserves of rock salt doubled following this discovery and are now thought to be some 117 km³. Later, following the proposals of Warrington *et al.* (1980), these horizons became known as the Northwich (Lower Keuper Saliferous Beds) and Wilkesley Halite Formations (Upper Saliferous Beds). The highest three formations of the group, were named the Wych Mudstone, Wilkesley Halite and the Brooks Mill Mudstone by Wilson (1993), and are relevant to the Arclid area.

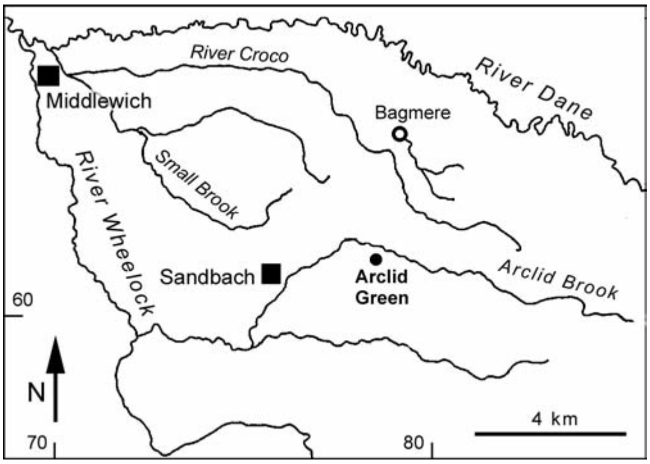


*Figure 2*. *The modern drainage network around Arclid.*

## Brines and subsidence geomorphology

Although industrially-induced subsidence has tended to dominate attention, there remains the fundamental geological process of saliferous beds interacting with a zone of ground water circulation on a geological timescale. Indeed globally, mobile groundwater interacts with rock salt, has undoubtedly been active through at least the Phanerozoic and continues at the present time. The saline ground waters so produced, ultimately feed natural brine springs which are normally located at the level of the contemporary river floodplain. In the eastern Cheshire Plain, natural rock salt dissolution has probably contributed to overall land surface lowering from before the Quaternary and of course this activity continues today. The earliest known written record of natural subsidence is attributed to John Leland, the pioneer Tudor antiquary, who in 1533 reported on 'a sinking as having occurred near Combemere [SJ 590446, 5 km NW of Wilkesley], and the formation of a pit containing salt water'- quoted by Calvert (1915). During the period of extensive industrial brine abstraction, the natural cycle of brine creation was masked, but this century it has largely reverted to its former relatively low rate. An analysis by Earp and Taylor (1986), in the Chester and Winsford Geological Survey memoir, presents an excellent overview of the topic along with a discussion of the problems which confront the field geologist.

The first comprehensive insight into the relationships between a rock salt bed outcrop and allied subsidence was given by Taylor *et al.* (1963) in the Geological Survey Memoir describing the Stockport and Knutsford region and Evans (1970). They emphasised that in the humid British climate, rock salt cannot crop out in the normal way because of its very extreme solubility. By weight, the solubility of rock salt is 35.5%, making it 7500 times more soluble than limestone. Hence, the rock salt beds necessarily lie at depth, with their upper terminations characterised by undulating surfaces, occasionally with entrenched channels (Fig. 4). In an equilibrium state, this surface corresponds to a front determined by the lower limit of groundwater circulation; above a thin zone of saturated

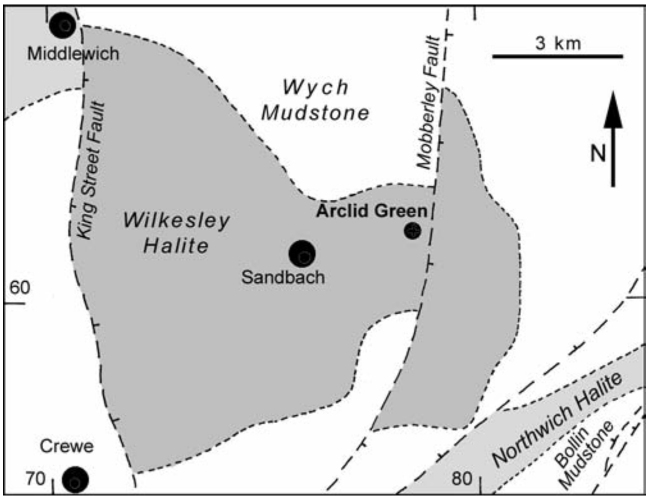


***Figure 3**. Bedrock geology of the region around Arclid (after British Geological Survey).*

brine, the rock salt has been taken into solution. The front, the upper surface of the rock salt, is referred to as the 'wet rockhead' and this is overlain by a zone, which can vary between 65 and 160 m thick, of a dissolution breccia of mudstone. This comprises a residual unit of broken and collapsed material that typically is brecciated and permeable. It is derived from non-soluble sediments that originally overlay or were components of the halite formations. Some brine filled cavities are present, especially towards the base of the breccia. Technically the collapsed unit should be regarded as a superficial deposit as the material is no longer *in situ*.

Usually the rock salt bed and confining mudstones have a dip, and this factor has an important bearing on the aerial extent of active subsidence processes. The relationship is best illustrated by a sketch cross section (Fig. 4), which demonstrates that where a younger *in situ* impermeable mudstone formation is present, the uppermost rock salt is beyond the reach of circulating ground water. This is designated a 'dry rockhead', though it is not true rockhead as it is not overlain by unconsolidated surficial sediments. Thus the dry rockhead of the Wilkesley Halite corresponds to the base of the undisturbed Brooks Mill Mudstone.

Industrial pumping of the saline ground water within the collapsed zone, has lead to the development of a local 'brine run', effectively a concentrated flow of brine along the top of the wet rockhead, and this converges upon the abstraction point. In turn, this artificially enforced brine flow leads to fresh water entering the system from the surface to replace the pre-existing brine. Inevitably, the introduction of fresh water triggers the aggressive dissolution of the wet rock salt head and attendant enlargement of the 'brine run'. Following progressive reduction in the strength of the bridging roof material, collapse ensues, and subsequently this extends upwards through the breccia to cause linear subsidence at the land surface. These 'brine runs' commonly follow the strike of the halite and can be traced from the brine abstraction point outwards for at least 8 km. It is likely that some tributary runs develop without any surface expression, but these invariably have their upstream ends where surface water is able to enter the system. They result in areas of enhanced dissolution expressed at the surface by a circular collapsing landform or doline subsidence.

## The Arclid area geology

The regional relief and drainage is shown in Figure 2. Around Arclid the general altitude is around 75 m OD. Arclid Brook rises below the ridge forming Congleton Edge and flows WNW for 7 km to Arclid, where it turns SW through Sandbach for a further 4 km, to join the River Wheelock, which in turn joins the River Dane at Middlewich about 9 km NW of the study area.

The Arclid vicinity was re-mapped by Wyndham Evans of the British Geological Survey in 1957 during the revision of the Macclesfield One-inch sheet 110 (Evans *et al.,* 1968). The bedrock was assigned to the basal Wilkesley Halite ('Upper Keuper Saliferous Bed'), and this formation, with a conjectural thickness of around 100 m, was inferred to form part of a westward plunging shallow syncline. Beneath is the Wych Mudstone Formation. The sequence was thought to form a block some 8 km wide sited between the roughly north-south trending King Street and Mobberley faults, both of which are major antithetic faults downthrowing to the east, contra to the major extensional growth faults. With a cumulative normal throw of over 4000 m, these faults of the Wem, Bridgemere and Red Rock Systems define the eastern limits to the Cheshire asymmetrical half graben. Evans invoked the presence of saliferous beds immediately beneath the superficial sediments seeing these reflected in the geomorphology. Taxmere, a small lake

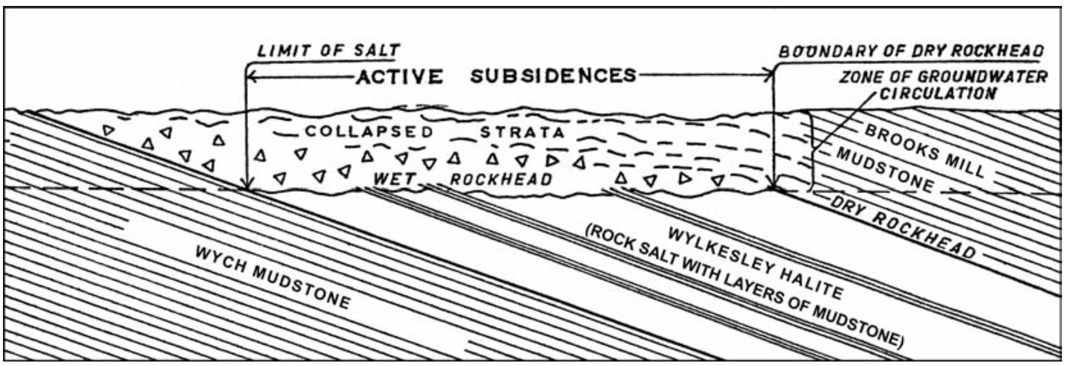


***Figure 4**. Diagrammatic representation of the relationships of a dipping salt bed to the salt sub-crop with zones described as dry and wet rockhead (after Taylor et al., 1963).*

occupying a hollow just beyond the old Arclid quarry limits was interpreted as a likely crater-type (non linear) salt subsidence.

The immediate area is underlain by unusually thick Quaternary sediments, with a formal lithostratigraphy following Worsley (1999). The cap unit, the glacigenic Stockport Formation, consists of thin patchy sands over an extensive till sheet with fluvioglacial sand lenses, giving a maximum thickness of some 12 m. The shallow valley of the Arclid Brook cuts through the glacigenic cover sequences where it forms the southern boundary of the old quarry. On its floodplain several boreholes were sunk by Sandbach Urban District Council c1940 around SJ779621. These revealed over 20 m of a sand dominated sequence significantly forming a **fresh** water aquifer. This potable water was abstracted for use by the local community (from 1946 the local Water Board) until the boreholes were abandoned in 1963, after which Bathgate Silica Sands commenced quarrying on the adjacent land. The initial quarry exposures (above the water table) showed that beneath a thin till, up to several metres of sands rich in comminuted coal and northerly derived gravel erratic clasts, lay unconformably on sands which were deficient in the 'glacial' clast lithologies and clearly not sourced by glacier meltwaters. These lower sands were assigned to the Chelford Sands Formation (Worsley, 1966), later called Chelford Formation, and this includes the Congleton Sands (Middle Sands) (Evans *et al.,* 1968). A decade later, as the quarry expanded, there was a change from dry to wet sand extraction in order to work the full thickness of the sands below the ground water table. This was achieved by suction dredging from a pontoon floating on an ever extending lagoon. Careful washing of the raw sand was necessary since the deeper (unseen) sands included the Arclid Member, a sequence consisting of beds of organic deposits, including fragmentary sub-fossil wood and peat clasts, both of Quaternary aspect.

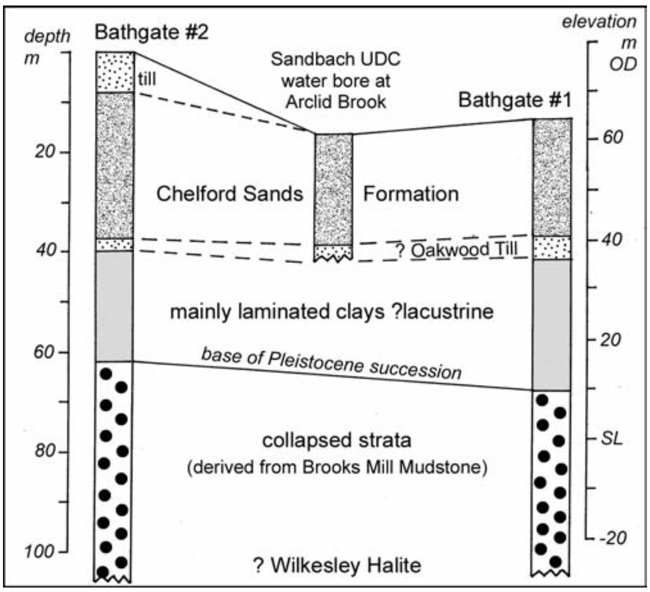


***Figure 5**. Logs of the Bathgate A and B boreholes.*

Subsequently, several radiocarbon age estimate assays on the sub-fossil organics were undertaken. These were discussed by Worsley (1980), who concluded that they had an age beyond the limits of that dating technique. Also, from a depth of at least 27 m, the pump picked-up a mammoth tooth with organic mud embedded in the cavities and from the latter a pollen spectra was extracted. This was identified and interpreted by Michael Keith-Lucas as being of probable Last Interglacial (Ipswichian) character, (Worsley, 1992). It may be part of the Arclid Member.

The predicted presence by the Geological Survey of the Wilkesley Halite beneath the Arclid quarry led to concerns by Cheshire County Council over possible problems arising from the reactivation of rock salt dissolution by escaping lagoon water. Since both planning permission for expansion of the site and a switch from dry to wet working were dependent upon these fears being allayed, two specially commissioned deep boreholes were sunk for the quarry company in 1971 some 400 m apart. These yielded an unexpected insight into the deeper Quaternary geology.

Bathgate No 1 (107 m deep) was located on the floodplain of the Arclid Brook immediately W of Near Arclid Bridge close to the A534 road (SJ783619). It penetrated 48 m of superficial sediments, and terminated at a depth of 59 m in collapsed debris derived from the Triassic bedrock. Unfortunately, coring only commenced at a depth of 24.3 m, i.e. within a basal till unit. Above that depth, the log is based on the examination of samples in the bentonite drilling fluid collected at 1.5 m intervals. In contrast Bathgate No 2, located 500 m NNW of Arclid church (SJ774620), was close to the lagoon within the active quarry. When this borehole was sunk the overburden had yet to be stripped, and hence it first had to penetrate the Stockport Formation. In all 62.2 m of Quaternary deposits were proved and below the unconformity, 62 m of collapsed mudstone breccia were proven before drilling was terminated. In Plant *et al.* (1999), reference is made to the source of a sample of Wilkesley Halite used in their Cheshire Basin study as being from an Arclid Bridge No 2 borehole. Its location is identical to that of Bathgate No 2, and it is known that the British Geological Survey examined the cores. Also the writer saw several halite cores at the quarry. This suggests that the top of the Wilkesley Halite was proven. Logs of these boreholes are shown in Figure 5.

Bathgate No 1 is closest to the centre of the Arclid Green study site, lying 800 m to the NW. Hence its findings are the most relevant here. Silica sands of the Chelford Formation are 24.4 m thick, and surprisingly are underlain by a further 23.7 m of unlithified sediments (Fig. 4). This lower succession comprised – (i) 3.7 m of till (? Oakwood Formation), (ii) 3.4 m laminated clays with silty/sandy partings, (iii) 11.3 m silty sands, and finally (iv) 5.4 m of laminated clay, sand and clay above the unconformity marking the top of the collapsed Triassic mudstones. Prior to drilling, the confirmed presence of glacigenic sediments below the Chelford Formation in Cheshire had been somewhat enigmatic, as in the Burland borehole succession (Worsley, 1970; Bonny *et al.,* 1986), but the new borehole revealed unambiguous evidence for an earlier glaciation in eastern Cheshire, although its precise age was indeterminate. A similar till was later seen at outcrop in the Oakwood quarry at Chelford (Worsley *et al.,* 1983). The presence of the unsuspected glacigenic sequence adds to the minimum total thickness of strata above the Wilkesley Halite. This, along with the collapsed mudstone breccia, gives a combined thickness of some 80 m.

## Subsidence at Arclid Green

With the approaching exhaustion of the old Arclid Quarry, a Chelford Formation silica sand resource beneath Arclid Green and Hall Farms some 1 km south east was proposed for development in order to supply fluidised sand by pipeline to the existing processing plant. The terrain at this new prospect possessed a much greater relief than the original Arclid Quarry site, and, being adjacent to the buildings of two working farms, there were sensitive environmental issues to be addressed. To minimise the impact, the proposed quarry design capitalised on the presence of a surface depression with a floor some 15 m below the average surface level in the vicinity. This had a plan form like a golf club head, consisting of an oval hollow and associated elongate trough occupying the eastern and southern parts of the site (Fig. 6). The depression afforded the possibility of both screening the overburden storage area from the adjacent land, and later after restoration, reclaiming what had before been poorly drained areas for agricultural use.

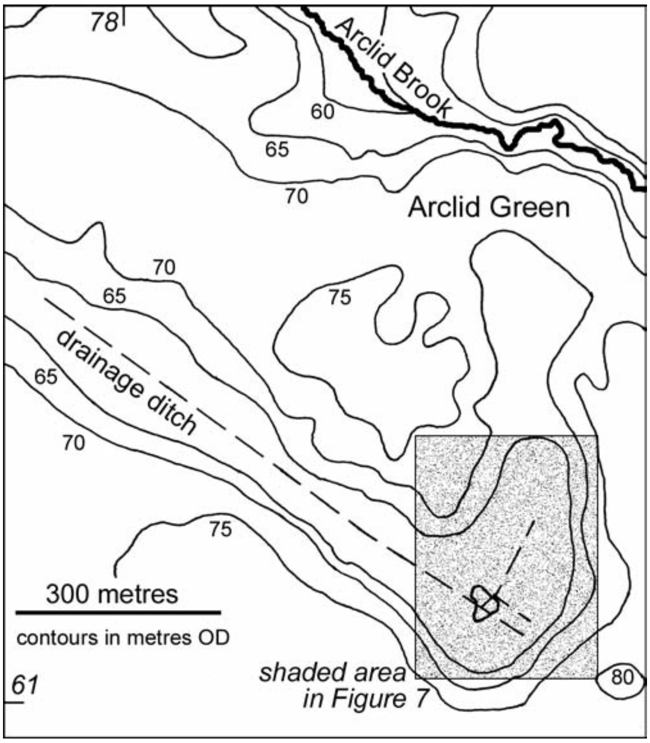


***Figure 6****. The Arclid Green study area with contours at 5 m intervals prior to sand quarrying activity. The peat margin on the valley floor extended to the 63 m contour*

A field investigation by the writer focussed on the nature and origin of the depressed area with special reference to any infill deposits. In view of the regional geology, particular attention was paid to possible indicators of salt dissolution subsidence and the extent of any low strength materials, e.g. peat, that might have accumulated, as it was proposed to infill the depressed area with quarry overburden derived from the stripped Stockport Formation capping.

The area formed part of the Arclid Brook catchment, but had no direct surface drainage connection with the brook. An artificial ditch system was present and this drained very sluggishly into an enclosed boggy area at the NW end. The 1:25,000 OS sheet SJ76, from 1960, revealed a closed 200-foot contour defining the lowest part of the depression at this location. The later (1979) 1:10,000 map SJ76SE, with metric contours at 5 m intervals, by chance fails to pick up the area of internal drainage. Another topographic low defined by a closed 61 m contour corresponded to the centre depressed feature. Thus, any excess water had to drain laterally through the subsurface sands as part of the local ground water flow. Active subsidence hollows are commonly marked by subsidence steps, simulating normal faults, and typically are some 1 m high. None was observed on the slopes at Arclid Green and this suggested that the area was currently stable.

Hand augering established that the floor of the area with internal drainage was underlain by peat. The 3-D geometry of the peat body was determined by augering along two levelled transects, NE-SW and SE-NW along the depression's main axes, supplemented by several other borings. Both Holman and Hiller hand-operated borers were used and these proved a maximum peat thickness of just under 16 m (mapped by 2 m isopachytes in Figure 7). It was estimated that there was some 300,000 $m^3$ of peat in the main hollow. In addition, two cased shell-and-auger holes were sunk and reasonably continuous cores were obtained.

The morphology of the hollow did not confirm or deny salt subsidence as the cause of the depression and its possible origin as a kettle hole feature could not initially be eliminated. Clearly the internal nature of the drainage was consistent with subsidence process having been active at the site in the past. Examination of the peat stratigraphy, in cores taken from within the main hollow, showed a very abrupt change in sediment character at the base and the presence of woody material low in the succession. In the absence of a classic tripartite late glacial succession of organic-rich/sterile/organic-rich sediments, the probability was that the peat was Flandrian in age. Over a decade later, when the peat fill of the linear trough was excavated during quarrying, the base of the peat was seen to encase Alder tree stumps in position of life, and this strongly suggested that a woodland had abruptly become flooded, again consistent with a post-glacial

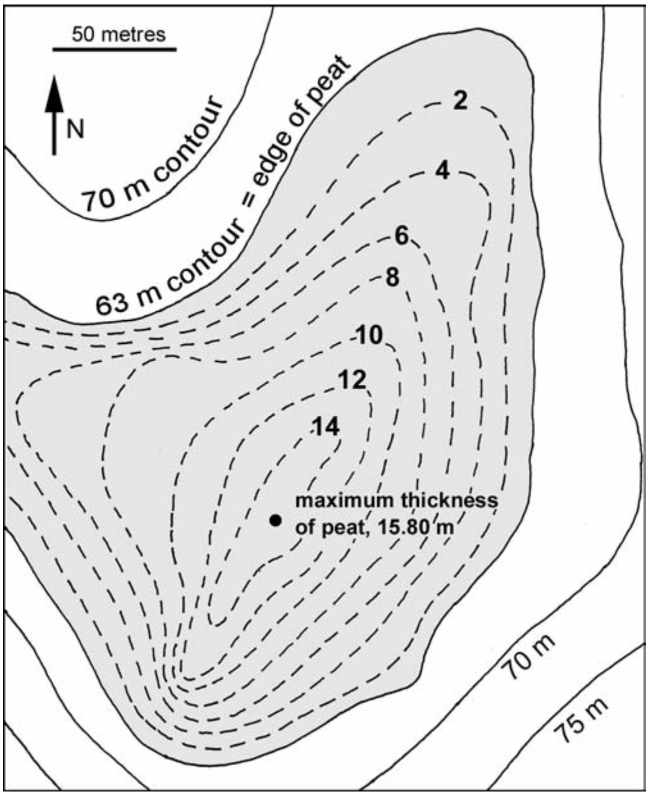


***Figure** 7. Limits of the main peat body within the Arclid depression. The 63 m contour approximated to the margin, but the peat surface formed a low dish with a surface low of 60.9 m OD. Peat isopachytes are drawn at 2 m intervals. Note the site of maximum peat depth of almost 16 m.*

age. After the hollow itself had been infilled by quarry overburden, exposures were subsequently created by quarrying through the marginal parts of the main hollow peat infill. Again the transition from the sands beneath to the peat above was fairly abrupt consistent with subsidence having commenced in the Flandrian rather than at the start of the Late Glacial. Furthermore, it could be seen that the original hollow form was not restricted to the glacigenic succession, since the basal Stockport Formation unconformity lay at a significantly higher level than the deeper parts of the peat infill. Finally, excellent exposures were created during dry extraction of the main sand body, revealed that the Chelford Formation (with included organic beds) and the till beneath were cambered at 22º directly towards the axis of the linear valley trough (Fig. 8). The till surface formed the working floor of the quarry. Together, these factors support the contention that the depression is a subsidence landform due to rock salt dissolution, rather than ice meltout. Otherwise it would have to be rather implausibly argued that a detached mass of glacier ice had somehow been intruded into the Chelford Sands prior to meltout and kettle hole formation.

## Role of glacial processes

Progressive subsidence has occurred over significant timescales and given the presence of halite at depth, it is likely that this process has some role in the enhanced accumulation of the Chelford Formation sands at the locality. However, the rate of dissolution will also have been influenced by the changing climatic environmental conditions. For instance, under the influence of meltwater drainage during glaciation it may have accelerated, while in contrast, if permafrost was present it was probably retarded if not static. The sub-superficial (drift) surface in the Cheshire Lowlands is complicated by a network of deeply incised channels, many of which appear to have undulating thalwegs and must have functioned as subglacial meltwater drainage systems (Howell, 1973; Howell & Jenkins, 1977). It should be noted that there is no way of determining whether these channels operated synchronously as an integrated system. At least parts of them may be inherited from earlier glaciations. Their incision is likely to have been rapid, and it cannot be assumed that glacial meltwaters did not directly erode the halite in places. Within these channels, thick variable sequences of porous sediment subsequently aggraded to later form conduits exploited by ground water flow. These circulating ground waters were probably saline, and flows were possibly increased when sea level was low during the cold stages.

A steep sided channel with a valley fill 102 m thick at Ettiley Heath (5 km WNW of Arclid) has been ascribed by Evans *et al.* (1968) to a 'glacial period of low sea level' by sub-glacial meltwater erosion (i.e. a tunnel valley). A drawn section following the base of the channel long profile has an average level of -50 m OD, and appears to be almost coincident with the wet rockhead above the Wilkesley Halite. This suggests that the expected cover of collapsed strata must have been largely eroded prior to aggradation. It was thought that this channel was traceable southwards (Rees & Wilson, 1998, with a rockhead map). It is stated that the buried channel base is at c52 m OD east

***Figure 8**. Working face in the new quarry showing the stratification in the Chelford Sand Formation dipping south towards the axis of the linear subsidence zone at 22º. Superficially this deformation looks like distal Gilbert-type deltaic cross bedding. The unconformity with the Stockport Formation lies at the stripped surface at the top of the face.*

of Crewe but has an undulating long profile. They also document pre-Late Devensian organic deposits within a complex sequence including several tills proved in boreholes at Stowford on the north side of the A5020 bridge over the Alsager-Crewe railway line (SJ735533), 4 km west of the M6, and demonstrate that at least part of the valley existed long before the Devensian. There is a possibility that the low rockhead surface below Arclid might link into this feature.

An additional factor is the role of the fluvial erosional system which presumably was initiated immediately after deglaciation. The outer part of the Arclid Brook catchment lies beyond the area with the halite sub-crop and the stream network as a whole appears unmodified as it extends across the halite zone. Progressive natural salt dissolution may have influenced the rate of down cutting but there is little evidence to suggest any major change of the stream pattern. The Arclid Green 'valley' may well have originated as a 'normal' tributary to the Arclid Brook, but later, progressive, linear subsidence, perhaps with crater subsidences, led to it being modified into its present form where the surface flow in the upper part of the tributary is reversed and the lower part is effectively abandoned. At Bagmere the local drainage shows an area of inward flow unconnected at the surface to the regional river network (Fig. 2).

Less than 5 km to the west, the area between Sandbach and Elworth has subsided as a result of extensive wild brine pumping that extended over several centuries (Fig. 9). Though extraction has ceased for the last 30 years, the question of whether any of the linear subsidences associated with brine runs extending into the Arclid area (Fig. 10) were accentuated in the historical period remains unresolved because of a lack of clear evidence.

### Palaeoecological investigations in Cheshire

That natural salt subsidence has been responsible for enclosed hollows formed in antiquity has been considered by some ecologists who have investigated the nature and origin of some of the Cheshire meres and peat mosses. A particularly good example is Wybunbury Moss at SJ697503 (Poore & Walker, 1958; Green & Pearson, 1977), where the adjacent parish church became so unstable that it had to be demolished apart from a buttressed tower. The subsidence feature at Wybunbury is dimensionally similar to that at Arclid Green but differs in that it has a central surface mire floating on a pond occupying a steep-sided basin some 15 m deep. In contrast, Birks (1965), favoured a kettle hole origin for Bagmere (SJ793643) where the fill exceeds 13 m, 'because of the relatively steep sides and the nature of the [sand and silt] minerogenic sediments'. Yet now appears that Bagmere, like Wybunbury Moss, is underlain by the Wilkesley Halite, increasing the probability that both are geomorphological expressions of subsidence that is related to dissolution of rock salt.

***Figure 9**. Houses in Sandbach affected by salt subsidence related to brine pumping from the wet rockhead on the Wilkesley Halite beneath 20 m of Quaternary sediments.*

## Subsidence at Upton Warren

Coincidentally, an earlier example of an important Quaternary fluvial succession having been affected by salt subsidence has been documented at the classic Upton Warren Interstadial type locality in Worcestershire (Coope *et al.,* 1961). This interstadial is conventionally regarded as being of mid Devensian age. In 1955, sagging of organic beds (Upton Warren Bed) by some 3 m was evident in the basal part of a gravel sequence c10 m thick beneath a low terrace of the River Salwarpe, a tributary of the River Severn. The deformation was attributed to salt subsidence, since a then-active saltworks lay within 1 km of the quarry at Stoke Prior. Mining of rock salt commenced in 1828, but soon the workings became flooded by an underground brine stream. Salt extraction then switched to wild brine pumping and continued until 1972. Judging by relationships on the levelled drawn section in their Figure 1, this subsidence may be at least in part syndepositional, and hence due to natural dissolution. Coope *et al.* also drew attention to a 'large subsidence with a lake' close to the Salwarpe near 'the Moors', although Poole and Williams (1980) later cast doubt on this interpretation of the lake, since a nearby

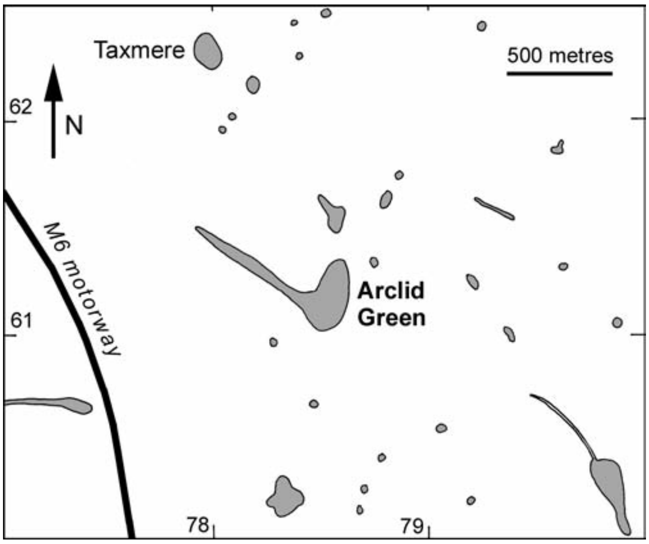


***Figure 10**. Probable salt subsidence features in the Arclid area (in part from a British Geological Survey data base).*

borehole failed to prove any rock salt beds. What is certain is that Upton Warren lies beyond the LGM ice limit and hence the direct influence of Devensian glaciation. It spans a much shorter time period and as such the setting is not directly comparable to Arclid.

# Conclusions

We may conclude the Arclid area surface morphology is consistent with the Triassic Wilkesley Halite forming the bedrock of the area. The depressed landform at Arclid Green appears to be primarily a product of natural Flandrian subsidence linked to dissolution at the wet rockhead at the top of the halite. Removal of the rock salt at this horizon must have removed support from the overlying mudstones that brecciated and collapsed. This appears to have been transmitted through the Pleistocene glacigenic Late Devensian Stockport Formation, the Chelford Formation and earlier glacigenic sediments. More generally, since the thick silica sands of the Chelford Formation appear to be preferentially preserved around Arclid, this suggests that dissolutional subsidence has been operative episodically at least through part of the middle Pleistocene and the Upper Pleistocene. It is considered that buried Late Devensian ice meltout, which could have produced a kettle hole, is unlikely to have directly influenced the present day geomorphology.

## Acknowledgements

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