Application of Aqueous Polymers on Earthen Substrates

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Executive Summary

Effective preservation of earthen architecture has eluded researchers for decades. While strides have been made in understanding the drivers of degradation and monitoring their effects, the impact of consolidation is still poorly understood. As a result, consolidation interventions at archaeological earthen sites are driven by empirical practice, with limited opportunities for quantitively evaluating treatment outcomes. The research presented in this PhD study contributes to addressing this gap in sector practice and understanding. A methodology is tested and used to examine the impact of consolidation on an earthen substrate through the application of a synthetic carbon-based polymer.

For this research, Fourier Transform Infrared (FTIR) Microspectroscopy is used to determine the depth of penetration of polymers applied to the surface of archaeological mudbrick and laboratory analogues. Polymer impact on compressive strength of analogues is measured with a Universal Testing Machine (UTM). Earthen architectural samples for this study were sourced from the Neolithic site of Çatalhöyük. This integrated approach of combining analysis of archaeological and analogous samples serves to verify the methodology and demonstrate its applicability to evaluation of other consolidants for earthen materials.

Results show that the perception of consolidation resulting from treatments involving surface application of polymers to earthen architecture at Çatalhöyük is erroneous. A polymer skin has formed which offers no improvement in the mechanical properties of this structural material, as confirmed by UTM testing of the laboratory analogues. These findings challenge conservators to re-evaluate their perception of treatments and examine the vocabulary of their practice. The case for further work in this area is clear and an investigative approach is proposed. This research highlights the need for evidence-based decision-making in conservation practice and discusses the difficulties in achieving this in the field.

The outcomes of this work have already made an impact on conservation practice. At Çatalhöyük, treatments for the earthen structures have been revised in the light of the findings reported here. Improved systems for monitoring of treatment effects and long-term stability have been developed. Importantly, conservators now understand the effect that decades of polymer application at the site has had on the structure and mechanical properties of the architecture. This insight underpins treatment strategies in the present and allows evidence-based planning for the future survival of the UNESCO site.

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Dedication

To Poppy Gale Meeklah

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1 Introduction

1.1 Research Overview

Heritage conservation does not occur in an idealised and standardised manner. The composition and condition of archaeological materials is highly variable with knock-on implications for the predictability of treatments. Materials and methods are not available universally. As a profession, it must be responsive and adaptable to circumstances. In-situ or field conservation adds a further level of complexity for the conservator who is likely to have a limited ability to control the environmental conditions and experience difficulties of access and a wealth of other practical constraints. In order to develop fit-for-purpose conservation strategies, treatments must be tested with material and environmental specifics on a case by case basis. Yet, too often, this cannot or does not happen.

The need for this study stems from the inherent difficulty in gauging the success of field applications of conservation treatments on archaeological heritage. Many practical factors inhibit a full analytical understanding of the impacts and constraints on field conservation treatments for archaeological earthen heritage. Often, preconceptions, anecdotal methodologies and ad-hoc practices perpetuate conservation methods without insight into treatment effectiveness. Additional problems compound when field treatments fail and there are no facilities or time to determine why they were unsuccessful. Equally challenging is that laboratory tests may omit aspects of real-world applications, which later prove to be crucial to the success of a treatment. There is also the reality of a conservation professional having to consider a vast number of variables to create successful treatment outcomes with limited evidence of successful intervention based on the specific variables after the fact.

The driver for this project arose from the author's experience at the Neolithic site of Çatalhöyük. One of the biggest challenges conservators face at the site is the preservation of the in-situ archaeology, chiefly the vernacular earthen architecture. Following the inscription of Çatalhöyük to the UNESCO World Heritage list in 2012, it became necessary to revise the site treatment strategy of consolidating the earthen surfaces with acrylic emulsion. This intervention had been intended to slow down the rate of deterioration and is a common strategy in the treatment of earthen architecture. In theory, it works through strengthening and solidifying the material by penetrating the interstices of the pores, where it solidifies.

It was common practice at the site from the late 1990's to use aqueous polymer dispersions on the archaeological earthen architecture. One material, Primal AC-33 (aqueous acrylic emulsion), became the 'fix-all' for both the mudbrick walls and clay plaster at the site. On excavation, many of the earthen buildings were sprayed, brushed or pipetted with Primal AC-33 so they could be left on open display (Cooke 2008). Primal AC-33 was phased out by the manufacturer and replaced by Primal B60A, which is the polymer system at the focus of this PhD study. Part of the annual conservation maintenance was the reapplication of Primal when signs of deterioration began to reappear. Due to discontinuity in team members and limited documentation of conservation treatments of the buildings, the concentration and application methods varied greatly over time.

1.2 Researcher Perspective

This author joined the conservation team at the Çatalhöyük Research Project in 2010. As Head of Conservation in 2012, after several seasons of reapplication, began to doubt the efficacy of the consolidation treatments applied to the in-situ structures. As I improved documentation and monitoring which evidenced that this intervention was not appropriate for this site. While a suitable alternative was being tested, the root cause of the treatment inefficacy needed to be identified. The laboratory tests discussed in this dissertation were designed to determine what impact the polymer has on an earthen substrate and to identify possible factors that contributed to this treatment's failure on earthen material at the site.

Though central, conserving the in-situ structures at Çatalhöyük is only one facet of my work at the site. I have worked collaboratively across research groups to balance interpretation, authenticity, visual significance, and appreciation of the site more broadly. However, these efforts have been met with substantial challenges. During my tenure at the site, I have seen two significant team transitions, first in 2012, with an abrupt team transition, then in 2018, the site took on both new leadership and team. As one of the few researchers who is still studying Çatalhöyük, I have a unique perspective on the impact of this kind of substantial discontinuity on a large-scale archaeological project. This situation has motivated prioritizing how conservation documentation is recorded and communicated, particularly for the in-situ structures.

Over the course of my time at the site, the benefits of reflexive practice have become starkly apparent, and become increasingly critical for conservation. I have gained an appreciation for preventative measures and sustainable heritage practices. Furthermore, my role at the site has shifted to include aspects of visitor interpretation and engagement. These perspectives would not have been possible in a shorter timescale. Creating a long-term future for Çatalhöyük is an ongoing process. The legacy of research and interventions at the site has had both positive and negative impacts. More often than not, successes were achieved through interdisciplinary partnerships.

1.3 Investigation Rationale

Consolidation is a simple enough concept, broadly the process of combining multiple parts into one; but in conservation practice, it is a complicated procedure to carry out. Despite recent advances in theory and practice, currently there are no products or methods available that have the necessary and requisite properties to consolidate earthen architecture. An ideal consolidant for mudbrick should have the following characteristics: (1) low viscosity/ability to penetrate deeply; (2) water-resistant but not water repellent in order to allow water migration both in liquid and vapor phase; (3) not form films on the surface nor show an abrupt planar boundary with respect to the untreated core; (4) resilient to stresses caused by salt crystallization, capillary rise of groundwater, and freeze-thaw cycles; (5) leave pores and capillaries open and allow for other impregnation, even with different products (re-treatability); (6) have both mechanical strength and abrasive resistance in dry and wet conditions; (7) allow continued thermal expansion coefficient similar to that of the material being treated (8) not change the colour or cause gloss; (9) durability; (10) easy application, including in damp conditions; (11) cheap and wide accessibility; and (12) most important, not be harmful to the operators (Chiari 1990).

Despite the lack of an 'ideal' consolidant, consolidation treatments *are* currently applied to earthen architecture. Given the necessity of compromise regarding consolidant properties, what is the effect of these treatments on the substrate material? This PhD study offers an analysis of specific consolidants that are applied to earthen heritage in a broad range of contexts. By reviewing historically treated earthen archaeological samples with a conservation protocol established using laboratory testing over 20 years ago, this study offers an insight into conservation practice as well as the unpredictability conservation practitioners face. By using standardized analogous samples, material performance of conservation practices is investigated in greater depth than has been possible previously. This research provides analysis and discussion of consolidant performance and balances conservation perception with measurable outcomes, challenging putative understanding of material behaviour using laboratory analytical techniques. Though there is no proven answer to the consolidation of earthen materials, this study sheds light on the risks of following empirical practice.

1.4 Project Aim and Objectives

This study aims to create a methodology for examining the impact of consolidation practices for archaeological mudbrick applied in the field.

This will be achieved by:

- Analysing previously treated archaeological mudbrick samples to assess penetration of consolidants.
- Measuring penetration into analogous samples of polymers commonly applied as consolidants.
- Measuring changes to physical properties of the analogues following polymer application.

1.5 Structure of the Thesis

Chapter 2 offers an introduction to the composition of archaeological earthen structures and their deterioration, including a discussion of how earth buildings are formed and what variables influence their preservation. Earthen architecture is made of a material with limited composite strength, no tensile strength, and is very susceptible to moisture, meaning that it has inherent problems with decay from the onset (Hughes, 1988). Chapter 3 addresses the challenges of working with earthen heritage in an in-situ context. While polymer-based consolidants seem like the most obvious remedy, the complexities of the material behaviour and environment make the solution more obscure. Chapter 4 provides the theoretical framework for understanding consolidation as it applies to earthen heritage. An overview of consolidation studies from the literature is offered. A discussion of the impact of consolidation carried out in the field, and the assessment of intervention outcomes are examined.

The case study for this PhD research is presented in Chapter 5. Çatalhöyük, like many earthen sites, is a complex exercise in preservation. Since it was first excavated in the 1960s, there have been efforts to preserve both the infrastructure of the site and the associated material culture. Over the years, evolving contexts of the site coupled with the legacy and perpetuation of specific treatment strategies have presented challenges to the long-term preservation of in-situ archaeology. Conservators try to create effective and sustainable treatment practices amidst evolving scientific understanding and limited team continuity. By examining treatment records and data evidencing patterns of deterioration at the site, investigation of significant means of preservation at the site can be addressed.

Chapter 6 presents the research methodology undertaken for this PhD research. Sample strategies are offered, followed by the procedures for Fourier Transform Infrared (FTIR) microscopy and Universal Testing Machine (UTM) experimentation. The results of the analytical work are presented in Chapter 7. Chapter 8 offers a discussion of the results, limitations of the study and the scope for further implications to the sector, and Chapter 9 concludes the thesis.

2 Archaeological mudbrick: composition and deterioration

If we are to do anything to reduce or prevent this loss of our heritage, we must first be able to characterise the material. We need to be able to describe the decay and to measure the extent and severity of decay. Only then can we hope to understand the causes and mechanisms of decay. Only then can we hope to understand the behaviour of any particular (material) in a given environment

Clifford Price 1996

2.1 Mudbrick composition and manufacture

Earth is one of the oldest known forms of building material, and all earth buildings have the same constituent parts: soil and water. Soil is typically composed of varying ratios of sand (50µm to 2000µm), silt (2µm to 50µm), and clay (less than 2µm). Sand and silt particulates have a small attraction for water because of their relatively small surface area compared with their volume, and for the most part, are non-plastic (Velde 1992). In the formation of earthen architecture, the proportions of the clay minerals and the specific types of clays (swelling or non-swelling), among other factors, will determine the properties of the final product (Velde 2008). There are many ways to form earthen structures and other materials are added to help mudbrick production or to improve the mechanical properties (Jaquin and Auqarde 2012). Earthen materials have been modified for use in architecture since the earliest times, with the addition of inorganic materials like gravel, lime, and gypsum, but also with a wide range of natural organic materials including plant matter, charcoal, and dung (Oliver 2008).

Mudbricks are easily adaptable objects made from just about any soil type. There is a fair amount of debate about what constitutes the ideal mudbrick recipe, with the average mixture reported as being within the range of 60% sand, 20% silt and 20% clay by volume (Brown *et al.* 1979). Some studies show that the composition can tolerate up to 40% silt without it diminishing the overall strength (Facey 1997; Kemp 2000). A complete de-cohesion of the earth can occur when very high-water contents are reached, if the earth has a high content of sand and coarse silt-sized fractions (Miccoli et al. 2014). The structural integrity of a mudbrick can be retained with as little as 5% clay, but an excess of 40% clay will cause it to crack (Love 2013).

Essential to the practice of building with earth is the principle that the materials forming mudbricks must dry into a homogeneous, compact mass without cracks. Earthen buildings materials can have quite variable clay content and it becomes necessary to include additional materials for added strength (Coffman et al. 1991) with vegetable matter, calcite and lime being the most common (Orazi 1995; Jerome 1993; Austin 1990). There is also variation depending on how structures are formed; rammed earth and adobe constructions have different grain size distributions and moisture content, even when coming from the same area (Ranocchiai et al. 1995).

2.1.1 Soil

Soils (non-clays) are particles with grain sizes larger than clays. Soil formation is dependent on dynamic processes influenced by climate, source rock, and geomorphology (Velde 2008). Soils are typically 90-99% mineral, with the remaining 10-1% comprising of organic constituents (Brady and Weil 2002). The non-clay materials are divided into two grain size categories of silt and sand which are, for the most part, non-plastic (ibid). Quartz is the most abundant material found in soils ranging from 40-70% of the composition, and when present as larger sand particles significantly impact overall friability (ibid).

2.1.2 Clay

Clay minerals are an integral part of earthen building materials, forming the smallest grain size portion of the material, clays also have specific mineralogical and physical properties that make them different from other common natural minerals. Clay minerals are composed of sheets of tetrahedral silicon dioxide (SiO_2) and octahedral aluminium oxide (Al_2O_3) linked through bridging oxygen atoms (Bleam 2017). On the aluminium oxide surface of the 'sheets' some of the oxygens are in the form of OH groups and there are OH groups within the structure as well. Broadly speaking, there are two main categories of clay minerals: those with one sheet each of the silicon and aluminium oxides and those with two sheets of silicon oxide enclosing a sheet of aluminium oxide (Shainberg and Levy 2005).

Clays are, at the same time, physically and chemically active. Clays are very complex minerals and exist in an endless variety with different characteristics. The clay platelets are held together by charge-balancing interlayer cations, and most clay mineral platelet surfaces carry a permanent negative charge due to the isomorphous substitution of lattice cations by cations of a lower valence (Fernandes et al 2012). When clay minerals come into contact with aqueous solutions, interlayer cations bound electrostatically at the planar surface and ion exchange may occur (ibid). There are swelling clays (e.g. smectites, montmorillonites) and non-swelling or slightly swelling clays (e.g. kaolinite) (Houben et al. 2004). Most of the earth used for construction has some tendency to swell and shrink and can also be a mix of several types of clay. Non-swelling clays offer little cohesion, resulting in weak covalent bonds; however, swelling clays offer high cohesion if high valency inter-layer ions are present (ibid). In both systems extensive cracking is inevitable, either when exposed to fluctuating environments (kaolinite) or during initial shrinkage after manufacturing (smectites). In weathering phenomena, there are several guiding principles one can use to follow or predict which minerals will be formed in any given setting (Velde 2008). The types of clay minerals formed are dependent upon the ratio of water to rock involved in the process and the type of rock involved. In initial stages of alteration, beginning with initial contact between rock and water, the rock has a strong influence on the clay mineral compositions and the clay typology present. Since rocks are chemically variable, the clay assemblages are also more varied (Velde 1992). Textural differences between structurally and chemically identical minerals affect their adsorptive and rheological properties.

2.1.3 Water

When combined with water, clays create pastes, slurries and suspensions by attracting water molecules to change their effective physical particle size. Clays take various chemical substances (ions or molecules) onto their surfaces or into the inner parts of their structure, becoming agents of transfer or transformation (Velde 2008). Clay is cohesive and acts as a binder for all coarser particles within the material's matrix, just as cement is the binder in concrete (Minke 2000). Cohesion between the individual clay particles is achieved through strong ionic bonds and relatively weaker hydrogen bonds. As water enters within the microstructure of the material, the hydrogen bonds are broken, forcing the clay particles apart and causing the soil to swell (Keefe 2005).

Water is an essential constituent of all assemblages of earth particles used as a building material. The behaviour of water and the impact of sorptivity (capacity to absorb or desorb liquid by capillarity) varies with particle size, polarity and shape; water has an impact on the process of manufacture, use, weathering and conservation of earthen structures (Warren 1999). There are two types of swelling with clay minerals in the presence of water: intracrystalline swelling and interparticle or osmotic swelling. Osmotic or interparticle swelling is experienced by all types of clay, but intracrystalline swelling is experienced only by expandable clays (Akoglu and Caner-Saltik 2014). Water interacts with clays in three ways: interlayer adsorption by the clay particle, out-layer absorption, and as free water. Since it is attracted into tiny spaces, it therefore exists in soils in the free (liquid) form, as captured water in inter-particle spaces and as physically engaged water locked in crystallisation (Figure 2.1). It is highly mobile rising through the earth correlating to pore size, position, and hydrostatic pressure (i.e. the smaller and higher the pore, the slower the rise), with water vapour travelling furthest and fastest (ibid) (Table 2.1).

Table 2.1 Classification of pore sizes (Brewer 1964).

Pore Type	Macropore	Mesopore	Micropore	Ultramicropore	Cryptopore
Size	>75µm	30µm-75µm	5µm-30µm	0.1µm-5µm	<0.1µm

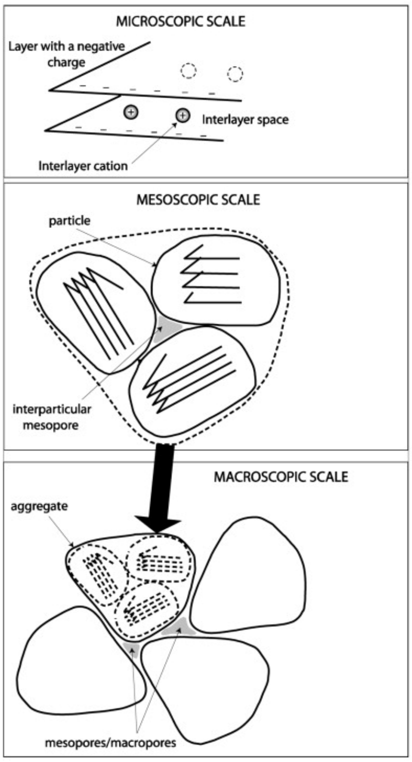


Figure 2.1 Multiscale representation of hydration for swelling clays (Salles et al. 2009).

2.1.4 Additives

Other additives used in the fabrication of earthen substrates as building materials vary greatly and are continually experimented with and improved upon even today (Landrou et al. 2016). Additives and modifiers to earthen building materials include both organic and inorganic substances including: sand, lime, hydraulic lime, cement, fly ash, brick dust, bitumen, or fibrous materials that reduce shrinkage such as plant extracts or mucilage, dung, saliva, water repellents like vegetable oils or animal fats, and synthetic organic polymers (acrylics, polyvinyls, and latex) (Oliver 2008). Stabilisers can also reduce the reactivity of the component clays through sorption, hydrophobic materials that prevent water from reaching the clays, and combinations thereof (ibid). Modifiers may also affect other properties of the earthen materials (whether good or bad) such as colour, reflectance, abrasion resistance, compressive and tensile strength, rigidity, water vapour permeability, and coefficient of thermal expansion (Warren 1999).

2.1.5 Assembly

The analysis of mudbricks and construction materials, in general, has provided insight in prehistoric and historic archaeology, and it is a common focus in conservation studies (Love 2017). Typically, once the blocks are formed, the material is left to dry in the sun; when the bricks are ready to be used, masonry techniques are employed with earthen mortar (Cooke 2008). Mortars differ from mudbrick based on the amount of water and other additives, but it is generally composed of the same earth (ibid). Other techniques include rammed earth or pisé, a technique where earth is built up in-situ; and wattle and daub, where additional wooden elements are added in construction. A point of clarification: the terms 'mudbrick,' 'adobe,' and 'earthen substrate' will only be used here for the description of building blocks made from air-dried earthen materials; these are not fired bricks.

2.1.6 Characterisation

Standard methods to characterise earthen building materials include particle size distribution, compactibility, shrinkage, plasticity, RGB colour, magnetic susceptibility, and acid digestion to quantify calcium carbonate. Some of these examinations can be carried out in the field, while others require laboratory analysis. Archaeological earthen architecture is a potential source of cultural information and can provide insights into chronology, technology, identity, labour, resources, and environmental conditions. Consequently, these aspects are widely studied (Love 2017). In architectural literature, the physical properties of mudbrick are defined by properties and characteristics significant to performance including chemistry, mineralogy, porosity, permeability, capillarity, cohesion, and erosion resistance (Hartzler 1996). Conservation literature also includes properties such as thermal dynamics, adherence, and shear strength (Warren 1999; Guillaud 2008; Velde 2008).

The purpose of understanding brick size and shape relates to questions of standardisation, the scale of production, and labour investments, relating to a greater understanding of technology and manufacture (Love 2013). Basic observations into technology can distinguish between coursed earth (e.g. cob, pisé), poured or rammed earth, or formed bricks of varying sizes. The different techniques have significant social implications as each method has different technical and labour investment requirements (Matthews 2005; Tung 2005).

Qualitative data derived from mudbrick analysis includes basic descriptions of surface characteristics, brick morphology (size, shape and individual brick dimensions), texture descriptions (i.e. silty clay, sandy silt) and colour. Qualitative data can also include visible indicators of construction technique or technology, inclusions, microscopic description of sand fractions and anthropomorphic micro-artefact identification using a portable digital microscope (Tung 2005; Love 2017).

The most common quantification methods for earthen substrates include mineral and geochemical identification using x-ray diffraction (XRD) (Rumsey and Drohan 2011; Tung 2005), x-ray fluorescence (XRF) (Emery and Morgenstein 2007; Goodman-Elgar et al. 2015), neutron activation analysis (NAA) (Kita et al. 2013; Nodarou et al. 2008), diffuse reflectance spectrophotometer (Balsam et al. 2007), Fourier-transform infrared spectroscopy (FTIR) (Friesem et al. 2011; Kita et al. 2013), and petrography and micromorphology (Goldberg 1979; Matthews 2005; Laporte et al. 2015; Mateu et al. 2013). There is no standard method for mudbrick analysis and the method of choice varies among researchers. Often, these analytical techniques depend on exporting archaeological samples to overseas laboratories (Love 2017).

Material testing for archaeological earthen heritage generally breaks down into two categories: field analysis and laboratory analysis. Field analyses are tests carried out in the field, mainly in the form of macroscopic observations along with simple manual tests that primarily rely on easily accessible and inexpensive equipment. By contrast, laboratory analyses are tests carried out in a laboratory with more sophisticated equipment pertaining to defined research questions (Guillaud 2008). The characterisation tests for earthen building materials most commonly referred to in the technical and scientific literature chiefly derive from geochemistry.

The literature covering the field of earthen construction typically refers to the use of field analyses for characterisation when new building materials are prepared. By contrast, the literature addressing architectural conservation refers primarily to the use of laboratory analyses (Hartzler 1996; Guillaud 2008). This dichotomy may reflect the different attitudes of the community of professionals dealing with new earthen building versus those dealing with conservation of earthen heritage, or it may be indicative of the resources available to each

(Guillaud 2008). There is a fundamental need to foster dialogue between these communities, as well as to improve the functional correlation between field and laboratory analyses (ibid).

2.1.7 Particle size distribution

Particle size distribution or texture is defined by the various fractions of particles in the soil (e.g. clays, silts, fine sands, coarse sands, gravel and stones) (Guillaud 2008). Most authors note the importance of particle size distribution in material performance and refer to several procedures for characterising this property. There are several methodologies for testing particle size distribution that can be carried out in the field, the most common of which is a simplified sedimentation test: a mix of soil and water is shaken and decanted in a flat-based cylindrical jar, indicating the quantity of the various particle size proportions deposited. Most silicates have about the same density (approximately 2.5 times that of water), grain size is a significant factor in settling, subsequently lighter/smaller grains settle more slowly. As clays are the smallest materials with regard to grain size, they tend to stay afloat longer and can be separated from bigger grains, then silt and finally sand (Velde 2008). Additional field testing methodologies include: visual examination of the rough texture of a soil in a dry state; taking the fine fraction after removing its coarser elements (stones, gravel, and coarse sand); testing by grinding the soil between the teeth, which allows one to assess the primary particle size component in sands, silts, or clays; the touch test, rubbing the soil between the fingers and the palm, which also allows one to assess the primary particle size component; and the wash test which, depending on how hard it is to rinse the soil off one's hands, suggests the primary particle size component (Houben and Guillaud 1984).

In the laboratory, quantitative particle size analysis is carried out by a refined process of sieving, measuring the rate of sedimentation to identify fine fractions of materials (e.g. < 0.08 mm) (Ashurst and Ashurst 1988; Teutonico 1988). American Society for Testing and Materials (ASTM) (2017) recommends the addition of a dispersing agent, sodium metaphosphate, to the clay fraction for the particle size analysis carried out in a solution of deionised water. A description of the soil particles can also supplement particle size analysis by examining it under a stereoscopic microscope (Hartzler 1996). This analysis enables one to determine the roundness and the spheroidicity of the particles, colour, and the presence of organic matter. Laser particle size instrument or light scattering (LS) is another methodology that allows for rapid analysis of grain size distribution, providing information on the volume of particles sizes from 0.04 µm to 2000 µm (Houben 1997).

2.1.8 Compactibility

Compactibility refers to the point at which the material reaches its maximum dry density, or optimum water content, under conditions of compaction; this provides information about the porosity and the permeability of the soil (Guillaud 2008). Field tests to gauge compatibility are qualitative and consist of compacting soil in moulds to make blocks, these are then pressed with an instrument such as a pocket penetrometer that provides a rough indication of the density of the soil. In the laboratory, compactibility is measured by the standard or modified Proctor Test, compacting soil of a known moisture content into a cylindrical mould of standard dimensions using a controlled magnitude (ASTM 2007). Conservation literature, however, suggests that analysis of this property has minimal importance for the understanding or prediction of the behaviour of earthen materials (Houben and Guillaud 1994). Shear strength is directly influenced by water content, while compaction increases density and strength to a certain point, after which there is no increase; incorporating the maximum permissible water content prior to compaction had more effect on the shear strength than did the amount of compaction (Webster 2008).

Capillarity, the properties of porosity and capillarity of the material is of particular significance regarding the conservation of earthen architecture, as indicative of the material's susceptibility to degradation (Guillaud 2008), as well as receptivity to conservation intervention. The maximum water content is that of the field drained saturation of the natural material, which depends on its porosity and the absorption of water by the clay-sized particles. When sand is compacted, the average porosity is about 30%; when clays are compacted, the porosity is near 5%–10% (Velde 2008). As a result, the potential for compaction of clays in their natural state is much greater than that of sand (ibid). This phenomenon is due to the irregular sand particle shape compared to the sheet-shape of the clay particles. Subsequently, the relative proportions of the different grain sizes are an essential consideration in dealing with soil and earth materials. When more large grains are present, the more rigid behaviour of the sample - and there will be a stronger tendency to deform the material by grain breakage (ibid). Capillarity is a critically important factor contributing to damage in mudbrick, having the potential to transfer soluble salts through the blocks to points where evaporation and crystallisation cause extensive physical damage.

2.1.9 Shrinkage

Shrinkage refers to the property of soil to change in volume in the presence of water, this procedure provides a preliminary indication of the quantity of clays present, and of how active or unstable (montmorillonites, smectites, and bentonites) they will become (Hartzler 1996). In the field, shrinkage is evaluated by using moulds to form disks of fine soil < 0.4 mm, then measuring the reduction in the diameter of the disk compared to that of the mould (Guillaud 2008). In the laboratory, a soil linear shrinkage test is used, measuring the impact of temperature on linear shrinkage (ASTM 2008). Relative shrinkage (RS) can also play an essential role in understanding shrinkage behaviour; this is the product of the difference between the liquid limit and the shrinkage limit, multiplied by the bulk density, divided by the density of water (Demehati 1990). The result of this equation, in percentages, gives the measure of this relative shrinkage; thus, for RS ≥ 70%, soils that shrink a great deal; for 50% ≤ RS ≤ 70%, soils that shrink moderately; and for RS < 50%, soils that shrink very little (ibid).

2.1.10 Plasticity

Plasticity relates to the behavioural properties of soil in the presence of water. This property is difficult to assess through field analyses accurately, however a standard proximal test is the cigar or ribbon test, where a roll of soil (approximately 12 mm) is created, and then estimating its clay content by the length at which the 'cigar' breaks when it is rested on the palm and gentle pressure is applied (Guillaud 2008). In the laboratory, the Atterberg Limits Test is one of the most commonly carried out on earthen architecture and includes the liquid limit, the plastic limit, the shrinkage limit and the plasticity index (ibid). It is commonly cited in the literature and used in conjunction with ASTM standards (Houben and Guillaud 1984; Teutonico 1988; Demehati 1990; Hartzler 1996). With archaeological structures, collecting samples to perform Atterberg Limits testing can be difficult depending on in-situ regulations, as large samples may be required to obtain accurate results.

Deformation over time, or plastic behaviour, relates to the load pressure of the structure exerted on the materials, resisted by the inherent strength of the material (Marshall et al. 1996). A field of research that seems to be rarely explored concerning ancient earthen structures is their physical stability as a function of time (Teutonico 1988). While stone and fired brick are resistant to plastic flow, and failures are due to internal cohesion or crushing strength, clay materials are subject to plastic flow or deformation that is not limited in time (Velde 2008). Cohesion refers to the capacity of particles to bind together and the bending strength of the coarse fraction (Guillaud 2008).

2.1.11 Colour

Colour is the most visually distinctive characteristic of mudbricks and can aid in establishing origins of sediments (Morgenstein and Redmount 1998). Colour is a simple qualitative variable that provides information about sediment composition (Goldberg and Macphail 2006) and various chemical processes, including weathering, oxidation-reduction and decomposition of organic matter. Colour is affected by aerobic or anaerobic conditions, and colours of buried sediments become lighter, yellower or redder. While red, brown, grey and yellow are all qualitative descriptions of soil colour, they are not useful for quantitative comparison. The Munsell Soil Colour Chart is the standard for describing sediment colours and allows for direct comparison of soils anywhere in the world (Oliver 2000; Love 2017), however, the use of Munsell Soil Colour is also highly subjective. Establishing colour parameters can be useful in conservation treatments, as a gauge for the use of new materials that are of a similar colour to original fabric (Joseph and Vasquez-Urzua 1995), or if the intervention causes a noticeable colour change.

2.1.12 Geochemistry

Geochemistry is a useful approach for looking at the composition of earthen architecture; this approach is particularly relevant to archaeological earthen architecture, as historical or local information about composition is unavailable. Methodologies such as magnetic susceptibility, acid digestion, loss on ignition and particle size distribution are used to look for variability and possible connections to social implications tied to the fabrication of earthen buildings (Love 2017). Magnetic susceptibility can be carried out in the field with a magnetic susceptibility meter. Acid digestion is done to quantify calcium carbonate, a common element of earthen tempers. Similarly, loss on ignition quantifies the amount of organic matter content, as well as $CaCO_3$ equivalent content present in brick materials (ibid). Shrinking and swelling are correlated with clay mineralogy in the soil, as a means to further the understanding of the textural and structural modifications associated with wetting and drying (Newman 1987).

2.2 Building with earth

The popularity of earth as a building material is easy to understand as there are many advantages of mudbrick; it is cheap, it has incredible insulation properties, and it can be shaped into many different forms (Norton 1997; Oates 1990). There are essentially two processes used in creating archaeological structural earth components. One method is to mix the earth with water to create a liquid state, formed into the desired shape in a mould, then allowing the water escape by evaporation. The result is a basic mudbrick or adobe block (Velde 2008) that can be fitted into place with an earthen mortar (soil slurry mixture of differing composition) (Figure 2.2). The second method is to slightly dampen the earth to the desired state, then the material is placed into a mould the size of the final desired object, then a high-energy impact is applied to compact the earth; this is called the rammed earth or pisé technique (ibid) (Figure 2.3). The two different forms can generally be identified by variations in size, mudbricks are characteristically smaller than rammed earth, as they are typically in large batches adjacent to the building site (archaeologically speaking). Rammed earth, by contrast, is often done in-situ as the blocks would require significant energy/resources to move. Both techniques can be found in one structure, particularly those that show signs of continued use and maintenance (Tung 2005).

The two building methods have significant implications for the final state and volume of the building materials. With mudbrick, loss of water shrinks the material into the final shape and volume loss can often reach 20%. Shrinkage must occur toward the centre of the object in the mould so that few cracks are formed (Velde 2008). The hardened, dry material must have a high crushing strength, as the individual elements produced by the process are relatively small in size and stacked, to produce the final building element (e.g. wall) (Tung 2005). The rammed earth method takes the opposite approach, by expelling the water by compaction pressure and causing the constituent grains to approach one another by force, the building element is near the final size of the object to be produced (e.g. wall) (Velde 2008). Here the desired mechanical strength is obtained by dynamic force and not by the natural attraction of the individual constituents (ibid). With such different approaches to building, it follows that component materials in the rammed earth and mudbrick methods would be different, including grain size and other characteristics. The expectation would be to see trends indicating clear choices by variations in grain sizes, components, and so forth to be different. However, at present, there is no real consensus as to which characteristics of earthen building materials most influence performance (ibid).

Figure 2.2 Mudbrick archaeological site of Moenjodaro, Pakistan. Photograph by Pascal Maitre (WHEAP 2012).


Figure 2.3 Stone (base) and rammed earth (upper) wall. Ksar of Aït-Benhaddou, Morocco. Photograph by the author.

Love (2017) points out that mudbrick compositions from antiquity are studied to preserve historic buildings. The conservation literature focuses on technique and method of construction for structural restoration and public display (Rainer et al. 2011; Sterry 2000). Several conservation reports conduct compositional analyses of mudbricks in an attempt to understand how to preserve and restore earthen monuments (Grimstad 1990; Torraca et al. 1972). In addition to the influential conference proceedings of the aforementioned Terra Congresses, there are two critical pieces of literature when referencing the study of earthen architecture, The GCI Terra Project Bibliography (2002), and the Terra Literature Review (2008). These two documents are designed to make the body of earthen architecture literature more accessible and aim to support research and training, and to facilitate interdisciplinary communication and collaboration (Teutonico 2008). The only shortcoming is that these are static documents, therefore exclude the last decade of research since their publication. The research covering earthen architecture can be divided into three general categories: the investigation of building materials, assessing the architecture, and finally, conservation methods. Typically, investigation of building materials uses quantitative methods, while architectural assessments are more qualitative. Historically, evaluations of conservation interventions have been qualitative but, with growing technological applications, more quantitative analysis is possible and is required to deliver evidence-based preservation processes.

2.3 Mudbrick deterioration (chemical and physical)

2.3.1 Mechanics

While earth is one of the most widely used construction materials in the world, it is also one of the most vulnerable. An intrinsic part of building with earth is the cycle of deterioration and repair that accompanies its use. The heterogeneity of earthen materials and construction systems makes it difficult to categorise and characterise the complex decay processes, and to formulate a general conclusion regarding the problems and treatment of earthen structures (Rainer 2008). The most common types of deterioration observed on earthen buildings and ruins is basal erosion, surface erosion, cracks and bulges, failure of the protective coating, upper wall displacement and leaning, and collapse (Crosby 1983). Deterioration patterns such as surface erosion and cracking typically have an underlying cause. As the chemical, geotechnical and environmental stresses change around the building, earthen materials swell and crack, creating a myriad of conservation dilemmas (Rico 2004).

General pathologies of exposed earthen architecture typically tend to manifest at the top of the wall, where erosion occurs if the wall is not protected by an adequate roof or shelter, and at the bottom of the wall if there is water penetration/infiltration, rising damp and salts from the ground that may migrate into the wall at the base (CRATerre and Doat 1983). The causes of deterioration are often classified as inherent when they can be associated with material composition or construction type and extrinsic when external factors such water, wind and other environmental and contextual factors play a role (Rainer 2008; Illampas et al. 2011) (Figure 2.4). The irreversible process of granular disintegration causes clay to become non-cohesive. Gradually, these mechanisms generate internal cracking and cause the particles of the material to lose their cohesion and detach from the rest of the body (Illampas et al. 2011). Disaggregation of earthen buildings also occurs when exposed to ultraviolet light, which can break down the molecular structure of clays, causing powdering or scaling (Fodde and Cooke 2013).

HP_002_1954.jpg
Photographer: YuTAKE Date Taken: 1954

HP_002_2003.jpg
Photographer: Louise Cooke Date Taken: 20/9/2003

Figure 2.4 The archaeological site of Ancient Merv, Turkmenistan. Site comparison from 1954 to 2003, showing significant loss (Cooke 2008).

Earthen structures are inherently challenging to conserve, as they present long-term conservation planning challenges. Relentless deterioration is common with vernacular earthen structures, regardless of the environment, as structures and in-situ archaeology deteriorate upon exposure to weather and other climatic changes (Matero 2015). Destabilisation can occur on both the macro and micro scale, exacerbating pre-existing conditions and creating new structural instability. On the macro-scale, potential forces of collapse can occur from precipitation events, wind, seismic activity, as well as plant and animal activity. On the micro-scale, surface desiccation results in shrinkage, cracking, loss of cohesion, delamination, and migration of soluble salts (Matero and Moss 2004). Changes in thermal co-efficiencies, including diurnal shifts, due to the presence of water and water vapour, will cause excavated surfaces to become climatically active. Salts present can either crystallise or hydrate depending on the environmental parameters, leading to disruptive internal pressure within the pores of the mudbrick. This continuous activity has a perpetual impact to the porosity and pore size distribution (Table 2.2).

Table 2.2 Possible effects of routine soil processes on pore size distribution (Nimmo 2013).

Soil Process	**Effect**
Shrinkage	Enlarged macropores New macropores created Within an aggregate, intra-aggregate pores decrease in size, or increase in size if clay particles shrink
Swelling	Decrease in the size of the macropores Close macropores Within an aggregate, intra-aggregate pores increase in size, or decrease in size if clay particles expand
Mechanical compression	Decrease in the size of the macropores Closed macropores Aggregates break up, reducing the number of intra-aggregate pores, thereby reducing the fraction of the pore space represented by the smallest pores
Disturbance from digging or ploughing	Existing macropores destroyed Interclod macropores created Aggregates break up, reducing the number of intra-aggregate pores, also the fraction of the pore space represented by the smallest pores
Biological activity	New macropores created Enlarged macropores, as by ongoing traffic of ants or burrowing mammals Decrease in the size of macropores, e.g., if they are affected by compression resulting from the expansion of a nearby root Increased aggregation, promoting the creation of interaggregate macropores, and possibly smaller intergranular pores within aggregates
Chemical activity	Constricted or obstructed pores, e.g. through growth of microorganisms Constricted or obstructed pores through formation of precipitates Enlarged pores through dissolution of precipitates Increased or decreased interparticle cohesion with complex effects on pore size and structure

Deterioration factors for archaeological sites are often of a different nature, related more directly to abandonment or excavation. Most earthen structures in archaeological contexts have lost their roofs and are, therefore, all the more vulnerable to environmental factors of decay. Excavation of walls is the cause of much deterioration (Liegey 1990). Structures that have long been buried have reached an equilibrium that is greatly disturbed at the time of excavation when rapid drying of the materials can occur, and weight loads are suddenly shifted (Rainer 2008). Exposure of archaeological earthen architecture poses tremendous difficulties for display post-excavation. The unique microenvironment created in the burial environment allows an overall thermo-hygrometric equilibrium to develop, but excavation then destabilises this process (Matero and Moss 2004). This microenvironment is created by a range of factors including the soil type, groundwater, depth and configuration, associated buried materials, and flora and fauna (ibid). Also, when earthen architecture has been burned, it compromises the structures of the clay in the soil. Once subjected to fire, the aluminosilicates that give clay its bonding strength become rigid and exacerbate fissures with cracking and shearing (Cooke 2008) (Figure 2.5).

Figure 2.5 Preferential deterioration of mudbricks within a wall linked to fire damage in antiquity, notably, however, the mortar remains un-cracked. Building 77, Çatalhöyük, Turkey. Photograph by the author.

2.3.2 Moisture

Moisture in its many forms is the most significant cause of deterioration in earthen structures, as fluctuations in the environment, as well as water. Although research has shown that earth-based building materials generally tend to absorb less water by capillarity than conventional masonry materials (e.g. fired clay bricks), the effects of moisture on adobe construction are far more devastating (Hall and Djerbib 2004). Moisture primarily affects the swelling clay particles, which are incorporated into the mixture composing the adobes (Salles et al. 2009). *Hygroscopicity,* the property of small-particle systems to take up moisture from the atmosphere through strong sorption forces on the particle surfaces, and capillary condensation, due to the lowering of the water vapour pressure above concave capillary menisci, will also cause deterioration (Gregorich et al. 2001) (Figure 2.6).

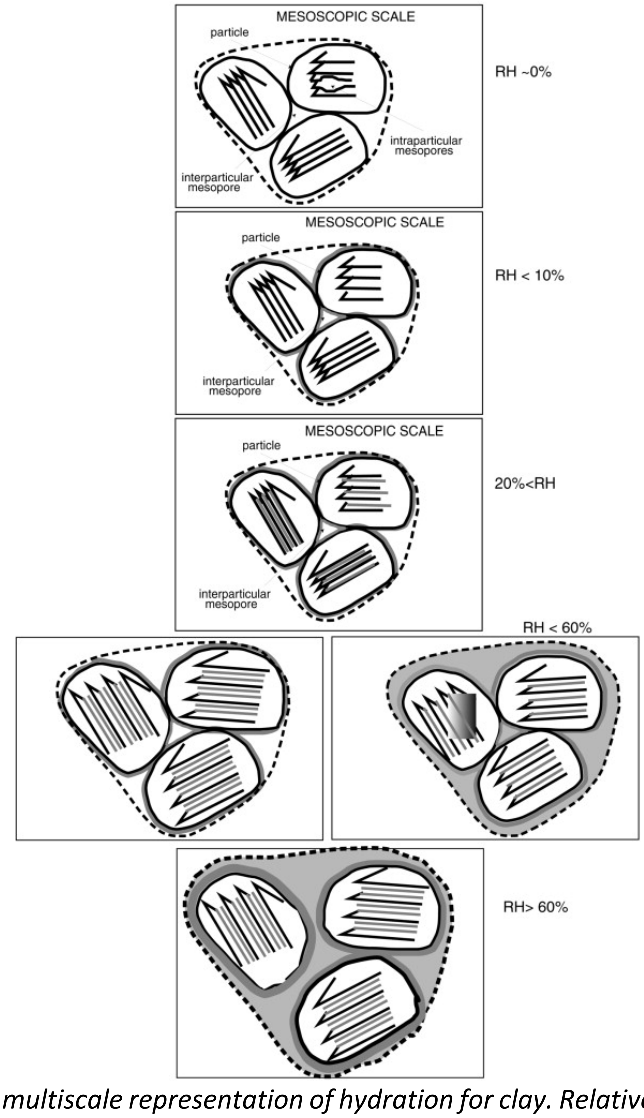


Figure 2.6 Atmospheric multiscale representation of hydration for clay. Relative humidity (RH), ranging from 0% to 60% and higher (Salles et al. 2009).

Wetting and drying are central in the formation of cracks in soils and clay-rich materials, wetting and drying cycles in soils tend to associate the clay particles into aggregates, forming cracks at their borders (Pillai and McGarry 1999). The wetting and drying cycle can lead to damage in three phases: first, saturation of the wall through rain; second, migration of soluble salts; third, crystallisation of soluble salts leading to efflorescence and surface erosion (Rainer 2008). Exposed structures are at risk from basal erosion, whereby a higher concentration of moisture in the lower part of a wall due to capillary rise leads to undercutting (Uviña Contreras 1998). Capillary rise is linked to deterioration through solvation and, later, desiccation of the particulates as well as salt migration/crystallisation (Figure 2.7). When atmospheric conditions enable excess moisture to be removed, individual clay particles are able to move back towards each other and to re-establish the hydrogen bonds. This action causes the overall volume of the soil to shrink and generates cracks (Norton 1997).

Figure 2.7 Undercutting due to basal erosion, exposure period from 2008 to 2014. Building 49, Çatalhöyük, Turkey. Photograph by the author.

A further mechanism by which trapped moisture may cause the disintegration of adobe bricks is cyclic freezing and thawing of water within the pores or just below the surface of earthen materials. The freeze-thaw cycle has a similar damage progression linked to the wetting and drying cycle: first, the saturation of the wall by precipitation; second, freezing of the accumulated moisture and humidity; third, crystallisation and expansion of the water (Rainer 2008). Low-temperature fluctuations (0°C to 4°C) can create specific added stress, as water attains its maximum density at 4°C, which is caused by the hydrogen bonding between the oxygen atoms that are negatively charged and the hydrogen atoms that are positively charged (Baldi et al. 1988). The result is added stress on the absorbed water within the soil matrix, creating differential pressure systems both in pore networks of varying sizes and within the clay particles as adsorbed water is unaffected (ibid). Dry materials are most vulnerable because the porous nature of earth allows the walls to attract moisture by capillary action from the ground. While a low moisture content in the wall is preferable, a well-drained, raised location will typically have better preservation than a low-lying, damp one (Pearson 1992). Freeze/thaw cycles lead to the development of increased pore pressures that gradually force the soil particles to lose cohesion and cause parts of the material to detach from the structure (Warren 1999). As the deterioration of adobe structures can be directly and indirectly correlated with the presence of excess moisture, successful preservation of most historic adobe structures depends on protecting these structures from water (Clifton 1977).

2.3.3 Soluble salts

While water itself can cause a range of deterioration problems, it can be particularly damaging when soluble salts are present. The salt cycle involves a sophisticated interaction between moisture and salts. Ground moisture dissolves naturally occurring salts in alkaline soils, then capillary action draws salt-laden moisture upward through wall bases (Rockstraw et al. 2014). Due to environmental differentiation, the moisture evaporates from the surface of the wall, typically just above ground level which triggers crystalizing salts to form on the surface (efflorescence) or within microscopic pores of the adobe (sub-florescence) (ibid). As sub-fluorescing crystals outgrow the surrounding pore structure, they exert enormous crystallization pressures on pore walls (e.g. sodium chloride has a crystallization pressure of 56 MPa) which can cause the substrate to break up (ibid). Salt crystals then fall to the wall base where they dissolve and increase the salt concentration, perpetuating the cycle (ibid) (Figure 2.8). Salts occur naturally in sourcing beds, or as later contaminants brought up by groundwater, or as surface pollutants caused by things like fertilisers (Goudie and Viles 1997). Moisture fluctuations create additional problems with the soluble salts commonly found within the earthen architecture; salts cause deterioration by way of efflorescence and sub-florescence (Goudie, 1986) (Figure 2.9). Constant hydration pressure is created within the walls when relative humidity (RH) fluctuates on either side of the hydration states of the soluble salts. The types of salts and the local environment are regionally and site-specific; those relevant to this study are discussed in Chapter 5.

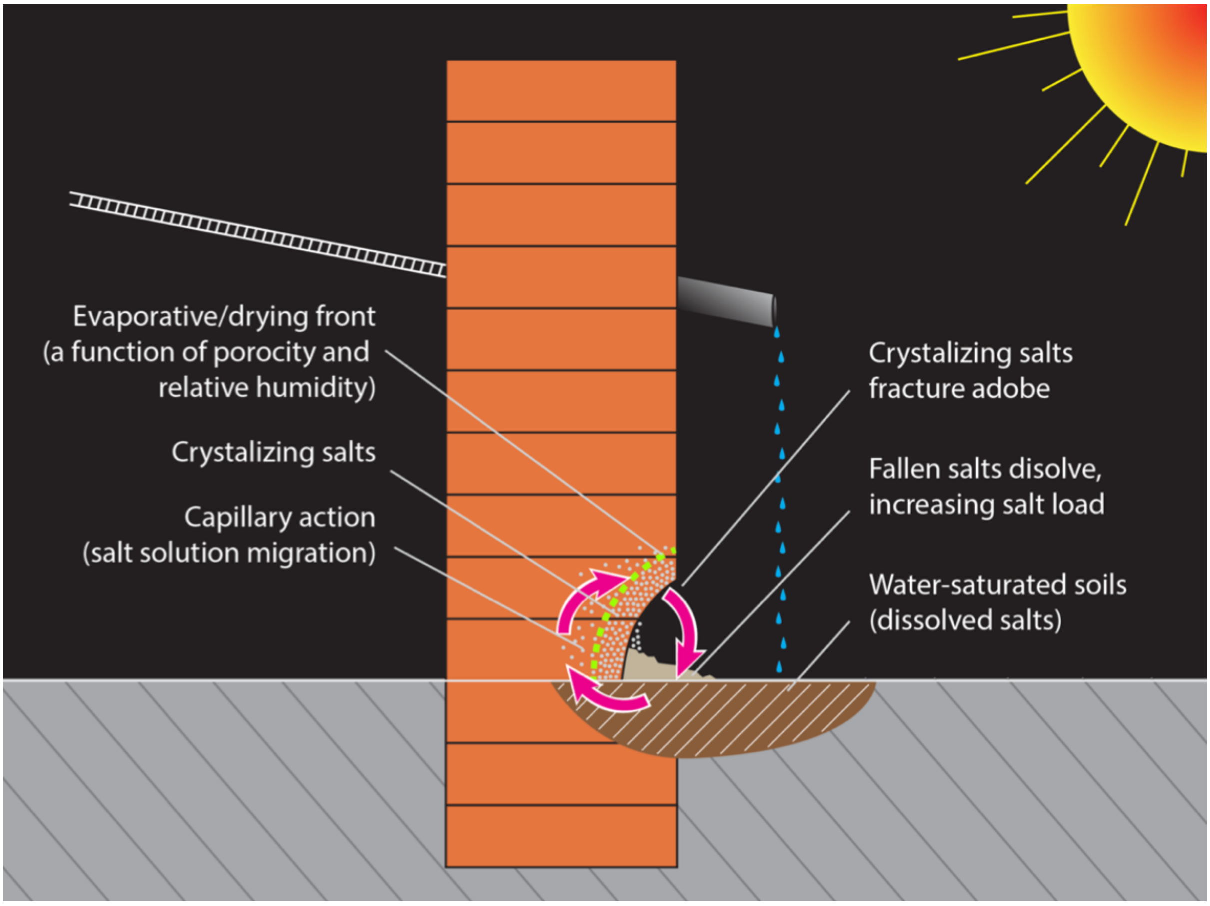


Figure 2.8 Diagram of salt cycle leading to basal erosion (Rockstraw et al. 2014).

Figure 2.9 Salt efflorescence on mudbrick wall, Çatalhöyük, Turkey (Photograph by King 2014).

Conditions such as high humidity or rising damp lead to soluble salts transitioning to the liquid phase (deliquescence), this liquid phase allow salts to migrate through the substrate by capillary action, finally, once the humidity drops below the deliquescence point the salt re-crystallises causing mechanical damage (Keefe et al. 2000). Although some argue that the degradation of the earthen matrix is primarily a product of the action of moisture on the clay particles, rather than the result of salt crystallisation, an examination of adobe samples from various earthen monuments has revealed that deteriorated adobe contains considerable amounts of soluble salts within its mass (Brown et al. 1979), as is also the case at Çatalhöyük, Turkey (King 2014). The added crystallisation pressure when the salts re-crystallise creates added mechanical stain within the pores and earthen structure. This finding may be considered as an indication that salt crystallisation occurs concurrently with other degradation mechanisms, thus speeding up the rate of decay. Multiple salts occurring together with varying deliquescence points, along with residual effects from hysteresis make predicting salt behaviour very difficult (Ebert et al. 2002). Dohene (2002) illustrates the complicated relationship of salts and related properties, leading to deterioration in the diagram below (Figure 2.10).

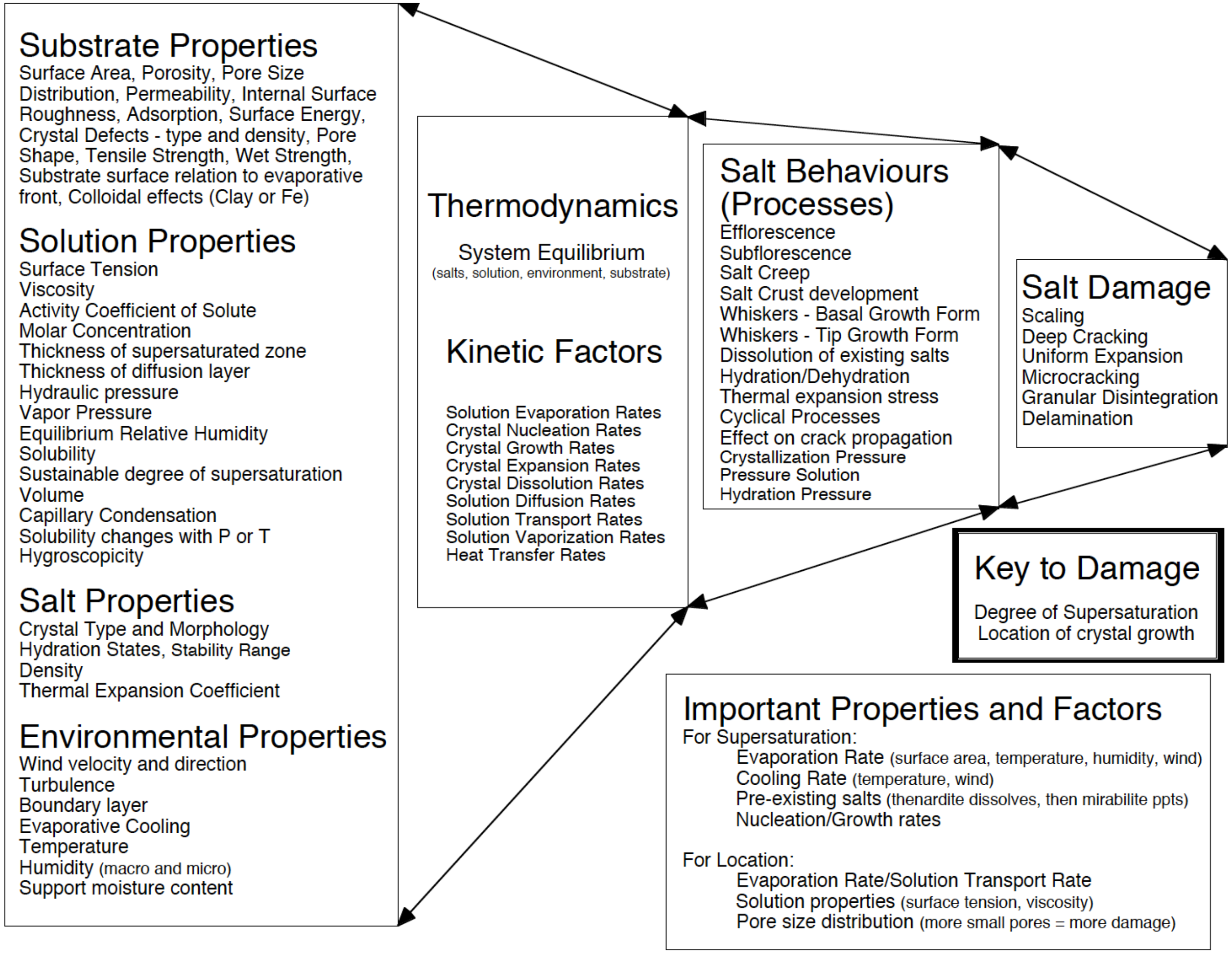


Figure 2.10 Diagram of properties, factors, and behaviours in the salt crystallisation process (Dohene 2002).

2.3.4 Manufacture

Deterioration can also be specific to construction techniques. The assembly can have symptomatic deterioration, for instance: pisé can show cracking at joints; adobe masonry may show deterioration if bricks and mortar are not compatible or if there is a lack of sufficient keying between the masonry and plaster layer, leading to differential erosion (Figure 2.11); wattle and daub may show deterioration of wood elements (Rainer 2008). As mentioned above, earthen materials deform plastically over time, which is also referred to in the literature as creep or settling (Velde 2008). The higher the proportion of clays in soil or earth, the greater the tendency to flow or display plastic behaviour, leading to more exaggerated features of settling (Crawford and Morisson 1996). Additionally, in excavated earthen structures, deterioration issues may be due to the materials in the soil layer itself, which might contain impurities that lead to salt efflorescence, biological growth, pH imbalance, etc.

Figure 2.11 Differential erosion of the mortar and mudbrick. The additional detachment of clay plaster (marl) through delamination and spalling. Small holes in the wall created by animal burrowing post-deposition, larger niches excavated and left unsupported creating sheering stress at the top of the wall. Building 132, Çatalhöyük, Turkey. Photograph by the author.

Horizontal movements and bending generated by earthquakes or ground vibrations, excessive deformations of the floor or roof structure, and soil or water pressures also lead to damage. Cracking or collapse of earthen structures is caused by horizontal movements, in-plane or out-of-plane bending of the walls, and support displacement (Illampas et al. 2011). The factors that influence the response of adobe buildings to horizontal loading and determine the extent of damage induced are: 1. the severity of the ground motion; 2. the geometry of the structure; 3. the interaction between the various structural elements; 4. the structural integrity of adobe load-bearing elements; and 5. the existence and effectiveness of retrofit measures (ibid). These movements apply to motion events in antiquity, during deposition or post-excavation.

2.3.5 Considerations

It should be noted that, usually, in an existing earthen structure, the disintegration of the structure cannot be attributed to a sole deterioration mechanism. Most decay processes take place simultaneously, and the disintegration of the material is a product of the combined interaction of several factors. The deterioration of adobe reduces the surface area of the material that can undertake loading (Illampas et al. 2011). In extreme cases, this reduction may lead to severe structural problems, since the bearing capacity of masonry walls may potentially be decreased (Hammond, 1973). Understanding which factor(s) is/are having the most significant impact is a critical stage in developing effective conservation interventions. Limiting physical damage by changing the behaviour of the archaeological substrate is one methods conservators try to approach treating earthen heritage. Consolidation, in theory, offers a way of making particles hydrophobic, preventing further water absorption and strengthen the earthen material. Assessing the effectiveness of a consolidation intervention, however, is challenging in a material as dynamic as soil.

3 Care of archaeological sites and challenges of working with earthen heritage in an in-situ context

Archaeological sites are constructed through time, often by abandonment, discovery, and amnesia.

Frank Matero 2006

3.1 Earthen sites as unique heritage

Although earthen structures have an inherent commonality in the materials and basic technologies employed to create the structures, their landscapes are vastly diverse in the geography, composition, form, and socio-cultural contexts (Bell and Kanan 2016:42). A universal construction material, structures made from earth appear in the oldest archaeological sites as well as in modern buildings, from large complexes and historic centres to individual structures and decorated surfaces (Teutonico 2008: vii). Each earthen archaeological site presents a unique set of challenges in terms of the complexity of deterioration factors that impact the architecture, the philosophy of conservation driving decisions, and the physical interventions that may be implemented (Oliver 2008: 80).

At microscopic and macroscopic levels, as well as is physical and social domains, earthen architecture is endlessly varied and thus engages a range of disciplines in the study, research, and practice associated with its conservation (Teutonico 2008: vii). Even the raw materials available (e.g. clay, soil) and building techniques (e.g. vernacular, adobe, wattle and daub, rammed earth, excavation) are vastly diverse and are widely defined across practitioners (ibid). As a result, every earthen landscape is unique and represents a special interaction between humans and nature (Bell and Kanan 2016).

The added variability inherent in archaeological earthen sites, in particular, make them difficult to holistically understand and subsequently preserve. Earthen ruins rank as one of, if not the most, enduring problems to be confronted, lacking the very architectural devices originally in place to keep them standing (Matero 2015:209). Often it is the enormous mass of many ancient earthen ruins that explain their persistence; however, even these will collapse over time from differential erosion, or eventually stabilize as formless lumps (ibid). Their unstable nature challenges these types of sites as sustainable heritage.

3.2 Defining care

The care of heritage is very broadly described as ‘safeguarding for future generations,’ an undeniably over-simplistic statement for an overly complex problem. Archaeological sites face many challenges: development, climate change, tourism, insufficient management, looting, conflict, inadequate governmental resources and lack of funding (Williams 2018). Despite improved methods for site preservation, an increase in heritage degrees at the academic level and greater ethical concerns at the professional level, interpretation of archaeological sites remains poor (ibid). These dilemmas create a very real problem of how those involved with heritage define and create practices for caring for in-situ archaeological heritage. When dealing with the highly friable nature of archaeological earthen architecture, as highlighted in Chapter 2, the problem is further compounded.

The guiding framework of heritage ethics concerns both the codes and principles that shape accepted practices with tangible and intangible culture, as well as much broader philosophical concerns around the legal, moral, and social implications of heritage (Ireland 2018). Arguably in today's global society, what creates ‘good care’ goes far beyond caring for the fabric of a site and must first create a holistic structure to support everything/one surrounding the site. Successful care of archaeological sites relies on management and conservation that can incorporate sustainable development (e.g. environmental, economic, social, and cultural) (Williams 2018). Heritage professionals must engage with stakeholders to consider what is excavated, what is left in-situ, and why. Preservation of archaeological sites in-situ should be coupled with a commitment to display and interpret. The fulfilment of an obligation to the future does not eliminate the responsibility to address the needs of the present (ibid). Arguably, many sites fall short of their obligation to the future due to poor planning as well as economic shortcomings.

3.2.1 Conflicting aims

For too long, the rift in archaeological and conservation practice limited how in-situ sites were managed. Fundamentally, archaeologists' interests lie in information and knowledge of the past; while conservators’ interests focus on preservation of the physical remains for the future (Demas and Agnew 2006). Due to a lack of investment in conservation that leads to the absence of solutions to address the formidable problems of deterioration, archaeology moved forward to fulfil its own needs and made do with whatever ad hoc solutions seemed appropriate for protection and preservation of the remains (ibid). Even in modern conservation practice, at each stage of the conservation process and with varying levels of intervention, preservation has become a series of entangled choices that fluctuate from practitioner to practitioner, leaving room for empirical methodologies to endure.

Strategies for successful care have to be organized long before the trowel's edge. Early planning facilitates the timely inclusion of conservation interventions — for example, risk management, monitoring, protective shelters, creating buffer zones, documentation, emergency preparedness, consolidation, structural treatments, and visitor management must be included in the overall plan. Ideological tenets of conservation philosophy such as reversibility, authenticity, and ascribing equal value to all things, are crucial to creating a dialogue about the conceptual value changes that conservators can make through intervention (Cane 2009). A multidisciplinary approach allows for the effective implementation of conservation measures, including prioritization of activities and funding (Henderson and Lingle 2018). While it is possible to preserve in-situ heritage in the long-term, practitioners must do so in a reflexive and adaptable manner.

3.3 Drivers for preservation

Why heritage professionals preserve things is something that is arguably taken for granted. There are many theories for what drives preservation of the past. It is widely recognized that society cannot move forward into the future unless it understands and acknowledges the past from which we come (Willems 2008). Things and places are contexts for human experience, constructed in movement, memory, encounter, and association (Tilley 1994). As heritage, archaeological sites are a mode of cultural production constructed in the present that has recourse to the past (Kirstenblatt-Gimblett 1998). Material culture possesses important scientific and aesthetic information as well as the power to inspire memory and emotional responses (Matero 2006). While explanations for the contemporary impulse to preserve are made in a number of fields, examining behaviours from the psycho-biological to the economic (e.g. tourists) to the sociological (the alienated 'man in the lonely crowd'), there is no simple answer to what drives humans what to preserve things and places (de Moraes Rodrigues 1998).

Heritage and conservation have become prominent themes in the discourse on place, cultural identity, and presentation of the past. Yet few archaeological projects have included site conservation as a viable strategy in addressing these issues, either before or during excavation (Berducou 1996; Matero 2006). Conservation itself can become a way of reifying cultural identities and historical narratives over time through valorisation and interpretation. It is essential to understand that the interpretation of sites is a contextual understanding relative to when it was uncovered and who carried out the interpretation. Therefore, sites need reinterpretation. Future interpretation depends on the survival of the heritage material as records that will be reread, but this cannot happen if the text has been erased (Podany 2006). However, there also must be some acceptance that current interpretation influences later understanding, and conservation interventions can also alter the information (Pye 2006).

For earthen sites, the drivers for preservation can be particularly complex. Though earthen archaeological sites offer abundant information about human building practices through time, the sites are difficult to conserve, and their often-non-monumental nature does not attract the same amount of interest as other building materials. Earthen sites are typically more remote than other types of in-situ heritage, as changes in landscape and the introduction of more robust construction materials transformed where and how people lived through antiquity. Distance from modern urban centres impacts many preservation factors, such as accessibility for researchers and tourists, access to conservation materials/equipment, and vulnerability to looters. Additionally, archaeological earthen sites are typically not places of mainstream religious significance and therefore do not have the added economic benefit of sites linked to some major religions. Some sites are able to generate other creative sources of funding, such as becoming filming locations or offering visitors immersive experiences (Figure 3.1). Like all sites though, conservation of earthen sites involves critical decisions regarding what is conserved and how it is presented, which are a product of contemporary values and beliefs about the past's relationship to (and use of) the present (Matero 2006).

Figure 3.1 UNESCO World Heritage Site of Ksar of Aït-Benhaddou, Morocco.The site has been inscribed since 1987 and has also been the backdrop to nearly two dozen Hollywood productions, all aiding in the financial viability of preserving the site long-term. Photograph: Ko Hon Chiu Vincent (UNESCO 2019).

3.4 Institutional framework

Overall, earthen architecture and its conservation are not well represented in academia. Earth is largely absent from courses on construction technology, design, architectural history, and preservation, because it is falsely viewed as a substandard building material (Avrami 1999). One of the critical reasons for this oversight is that earthen structures constitute a small fraction of new construction in the industrialized world. Consequently, there is no industry to support continued investigation of earthen materials and their applications (ibid). As such, the scientific and technological research base for earthen architecture and its conservation is minimal compared to that of stone, brick and timber. Research interest in earthen heritage has risen and ebbed over the last several decades. During the late 1980s and 1990s, considerable advancement of the earthen architecture conservation field was achieved through a series of training initiatives, international conferences, the formation of national and international committees, and a network of practitioners established through these opportunities for exchange (GCI 2006). Unfortunately, however, institutional commitment lagged along with support for larger scale initiatives and collaboration (ibid). Within the last decade, however, there has been renewed interest in new earth buildings due to their sustainability (Michael et al. 2016).

As with any conservation discipline, institutional involvement and cooperation are vital in developing the broad-based support needed for the conservation of earthen architecture. While there are now a handful of crucial well-recognized organizations that oversee research in earthen architecture, publication of their work tends to be found outside of the central conservation periodicals. Often methods and information are borrowed from other fields such as geology, agriculture and road building but significant differences in application often preclude a direct transfer of technology. Unfortunately, the result is a fragmented body of knowledge.

3.4.1 Professional associations

Over the years, several research bodies have formed to tackle the complex issues associated with earth as a form of building material. The most significant contributions have come from the International Centre for Earth Construction – School of Architecture of Grenoble (CRATerre-EAG), the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) with the formation of the International Scientific Committee of Earthen Architectural Heritage (ISCEAH), and the Getty Conservation Institute (GCI). In 1997, these institutions formally collaborated and established Project Terra (officially 2005-2008). The mission of Project Terra was to foster the development of earthen architecture conservation as a science, a field of study, a professional practice and a social endeavour. Through cooperative activities in the areas of research, education, planning and advocacy, the project members seek to advance the field in a variety of ways (Avrami 1999).

Traditionally, the conservation field has responded to this fragmented body of knowledge by organizing short courses related to the preservation of earthen architectural heritage, which emphasize the continuity of the tradition of building with earth (ibid). UNESCO's World Heritage Earthen Architecture Programme and World Heritage Programme on Earthen Architecture (WHEAP) aim for the improvement of the state of conservation and management of earthen architecture sites worldwide. These interdisciplinary research teams have generated volumes of literature that have brought great awareness to the study and preservation of earthen architecture globally (Love 2017). This is a relatively smaller and lesser-known subdivision of the larger UNESCO authority, as the unstable nature of earthen architecture makes it difficult to receive a designation. In recent years, researchers have begun to debate the merits and consequences of World Heritage (Meskell 2014). The politics of World Heritage is often at odds with preservation itself, due to international political pacting, national economic interests, and voting blocs through which particular states increasingly set the World Heritage agenda and recast UNESCO as an agency for global branding rather than global conservation (ibid).

A series of international conferences on earthen architecture conservation organized by ICOMOS, also with the moniker Terra, began in Iran in 1972. Thus far twelve international conferences have been held, the most recent in Lyon, France, in July of 2016. Each Terra conference has added to the body of earthen architecture knowledge by articulating the needs of the field, motivating particular activities, and promoting a network of practitioners around the world (Matero 2006). Topics ranging from conservation and management, local development, research and innovation, new dynamics, knowledge transfer and community projects, building capacity, to seismic retrofitting are presented and discussed through an interdisciplinary approach (Joffroy et al. 2016).

Another milestone in the field of earthen architecture conservation were The Pan-American Courses on the Conservation and Management of Earthen Architectural and Archaeological Heritage, known as the PAT courses (Balderrama 2001). These short courses were initially jointly organized by CRATerre-EAG and ICCROM in France; then later by CRATerre-EAG, ICCROM, the GCI, and the Instituto Nacional de Cultura in Peru, which ran from 1989 to 1999 (Avrami 1999). The PAT courses offered skill-building sessions in conservation, while they also advanced the entire field of study related to earthen architecture conservation. As with the Terra conferences, these activities have fostered the development of this field of study. The exchange between the global conferences and the specific educational activities has itself created important field projects, research initiatives, advocacy efforts and has increased institutional involvement (Balderrama 2001). Lamentably, while there are many other groups that offer short courses in earthen architecture, the PAT courses are no longer taught, though the GCI does offer region-specific training leading up to each Terra conference.

Within Europe there is growing trend towards in-situ preservation of archaeological heritage. First in 1969 with the European Convention for the Protection of Archaeological Heritage, then in 1992 as the Valetta Convention (Gregory and Matthiesen 2012), a series of international conferences were conducted to present research in the Preservation of Archaeological Remains In Situ (PARIS). These conferences also included nations outside of Europe, such as Australia, New Zealand, Turkey, and the USA (ibid). PARIS looks to take a multidisciplinary approach to four key topics: quantifying the degradation of archaeological remains and defining acceptable rates, long-term monitoring and mitigating studies, creating realistic multinational standards and legislation for monitoring and managing archaeological heritage, and documenting effective preservation strategies (ibid). Unfortunately, earthen architecture is a minimal component of the research presented at these events.

While interest in earthen architecture is currently on the rise, due to its sustainable building properties, there are still several problematic issues that need to be addressed. A significant benefit of renewed interest in building with earth is the resurgence of using traditional building and repair techniques coupled with new technologies and additives (Landrou *et al.* 2016; Michael *et al.* 2016). This renewed interest only tangentially benefits the conservation of archaeological earthen structures, and there is still no perfect answer to the long-term preservation of earthen structures. Generally speaking, it has been this author's experience that heritage projects are in a difficult position due to a wide variety of factors: shifting political landscapes, long-term viability, large numbers of stakeholders, finding and keeping funding/patronage, managing evolving scientific understanding, and keeping public interest. As a result, research projects are often piecemeal and short-term. Though having several years' worth of data collection is not uncommon, very few projects last longer than five years and even fewer of these incorporate both field and laboratory testing.

3.5 Conservation in an archaeological context

The current definition of conservation has emerged as a field of specialization concerned primarily with the material well-being of cultural property and the conditions of ageing and survival, focusing on the qualitative and quantitative processes of change and deterioration (Matero 2006). The current conservation ethos advocates minimal, opportune interventions, which can be retreated, often with either traditional skills or experimentally advanced techniques (Hölling 2017). This is a stark contrast to the conservation principles during the early 20th century when it was considered 'best practice' to restore artefacts, often irreversibly (O'Grady 2017). However, there is a practical element to the preservation of built heritage, which often requires more significant invasive intervention due to the need for greater visual legibility and structural reintegration. Modern conservation practice habitually looks to the material science of heritage, allowing chemistry and physics to guide conservation treatments and ethical constructs.

In some ways, conservation is at odds with excavation, as conservation focuses on the safeguarding of physical fabric from loss and depletion, whereas excavation is a subtractive process that is both destructive and irreversible (Matero 2006). While archaeology can decontextualize a site by representing it ex-situ in site reports and museum exhibits, site conservation represents and interprets the remains in-situ (ibid). Conservation planning and initial intervention in the field can determine the long-term survival and intelligibility of both moveable and fixed features (Pedeli and Pulga 2014). However, conservation is frequently an afterthought of the archaeological planning process. For earthen architecture taking a diachronic approach and utilizing multiples lines of evidence, including macro-morphological, mineralogical and chemical studies interpreted within the context of living vernacular traditions in the region, produces a nuanced understanding of the archaeological evidence (O'Grady et al. 2018).

The level of degradation associated with extant archaeological materials has a significant impact on any research. Therefore, the degree of stability directly influences methodological approaches to the collection and safeguarding of data relevant to multiple (both present and future) audiences (Caple 2000; O'Grady et al. 2018). Matero (2006) argues that archaeological sites are what they are by virtue of the disciplines that study them and are made, not found. With earthen sites, reburial is often the best choice for long-term preservation, but this is often at odds with archaeological research, stakeholder agendas and visitor access (Demas and Agnew 2006).

Display, as part of the conservation intervention, is a difficult challenge to successfully navigate in terms of practicalities and ethical practice. Both the moveable and immoveable heritages have inherent informational value and materiality, which should be expressed through conservation integrity; however, both are susceptible to change once the heritage becomes static. Integrity can manifest in many states such as completeness of form, physicochemical composition, or context. Often in conservation, it is expressed with authenticity or truthfulness of the original (Matero 2006). For archaeological sites, this issue is complicated by the measures for controlling preservation, for example: changing or manipulating the environment by reburial, changing the landscape by building a protective shelter on-site, or removing selected components such as murals or sculpture. While these are options that allow maximum physical protection and privilege the scientific/aesthetic value inherent in the physical fabric, the result is some level of de-contextualization. Conversely, interventions developed to address only the material condition of objects, structures and places of cultural significance, without consideration of associated cultural beliefs and rituals, can sometimes denature or compromise their power, spirit, or social values (Andrews and Buggey 2008; Genovese 2011). Ultimately, the situation for each site is going to vary, and the site's future will be chartered by a nuanced set of agreements and strategies. While there is no right answer to guide display practices, there are certainly wrong ones which generally arise from not having conservation input.

3.5.1 Conservation decision making

Institutional guidance for the preservation of heritage sites has been well established (Table 3.1). Though each document varies in emphases, the documents identify the conservation process as one governed by respect for the aesthetic, historical and physical integrity of the structure or place, requiring a high sense of moral responsibility. Implicit in these principles is the notion of cultural heritage is a physical resource that is both valuable and irreplaceable (Muñoz Viñas 2012). Conservation management of heritage sites is often complicated, and can be challenging to implement successfully, but it is essential regardless of whether or not a site has World Heritage status (Rodwell 2002). Even if the post-excavation plan is to rebury the site, a clear conservation strategy needs to be in place and not an afterthought.

Table 3.1 Conservation conventions concerning the preservation of in-situ heritage.

Convention	**Year**	**Impact**
Sixth International Congress of Architects in Madrid	1904	Early principles of architectural conservation, emphasizing the importance of minimal intervention, functional use for historic buildings and encouraging restoration according to a single stylistic expression.
The League of Nations Committee on Intellectual Cooperation	1922	The establishment of a number of national committees focused on international cooperation in a number of fields including archaeological research.
Charter of Athens following the International Congress of Restoration of Monuments	1931	Focuses on urbanism and the importance of planning in urban development schemes. Includes urban ensembles in the definition of the built heritage and emphasizes the spiritual, cultural, and economic value of the architectural heritage.
United Nations Educational, Scientific and Cultural Organization (UNESCO)	1945	A specialized agency part of the United Nations, whose constitution mandates the conservation and protection of the world's inheritance of books, works of art and monuments of history and science.
Venice Charter for the Conservation and Restoration of Monuments and Sites	1964	Codifies internationally accepted standards of conservation practice relating to architecture and sites. It sets forth principles of conservation based on the concept of authenticity and the importance of maintaining the historical and physical context of a site or building.
UNESCO Convention on the Means of Prohibiting and Prevention of Illicit Import, Export and Transfer of Ownership of Cultural Property	1970	Convention suggests that states declare some cultural property as inalienable to help prevent its export and, where necessary, facilitate its recovery. Additionally, states of origin can request assistance from other nations in recovering illegally obtained cultural property.

UNESCO World Heritage Convention	1972/ 1988	It promotes an international perspective on cultural heritage by inviting member states to submit an inventory of properties forming its national cultural and natural heritage to be included in a list of World Heritage sites. The convention encourages national efforts at protecting cultural and natural heritage and promotes international recognition and cooperation in safeguarding the heritage of the world.
Florence Charter on Historic Gardens	1981	Sets forth the principles and guidelines for the preservation of historic gardens. It outlines strategies for maintenance, conservation, restoration, and reconstruction of gardens, including their plans, vegetation, structural and decorative features, and use of water.
Ruins—Their Preservation and Display	1981	Sets forth strategies for the conservation and restoration of in-situ heritage.
ICOMOS (Washington) Charter for the Conservation of Historic Towns and Urban Areas	1987	Establishes the principles and guidelines for the protection and conservation of historic towns, designed to complement the Venice Charter.
ICOMOS Charter for the Protection and Management of the Archaeological Heritage	1990	Created in response to the increasing threats to archaeological sites worldwide, especially from looting and land development. Attempts to establish principles and guidelines of archaeological heritage management that are globally valid and can be adapted to national policies and conditions.
ICOMOS Nara Document on Authenticity	1994	Highlights the importance of considering the cultural and social values of all societies. Emphasizes respect for other cultures, other values, and the tangible and intangible expressions that form part of the heritage of every culture.

ICOMOS the Charter for the Protection and Management of the Underwater Cultural Heritage	1996	Outlines fundamental principles for the conservation of the underwater heritage and discusses issues of funding, research objectives, qualifications of the team members, investigation, documentation, material conservation, management and maintenance of the site, and dissemination of information about the underwater heritage.
ICOMOS Code on the Ethics of Co-existence in Conserving Significant Places	1998	Healthy management of cultural difference is the responsibility of society as a whole. In a pluralist society, value differences exist and contain the potential for conflict; and ethical practice is necessary for the just and effective management of places of diverse cultural significance.
ICOMOS the International Cultural Tourism Charter	1999	For the promotion and management of tourism in ways that respect and enhance the heritage and living cultures of the host communities, and to encourage a dialogue between conservation interests and the tourism industry.
ICOMOS Charter on the Built Vernacular Heritage	1999	Outlines the vulnerability of vernacular architecture. Sets forth guidelines for conservation practice, including research and documentation, preserving traditional craft and building skills, adaptive re-use, and the need for training to educate conservators and communities
ICOMOS Burra Charter	1999	A national charter that establishes principles for the management and conservation of cultural sites in Australia. The Charter is particularly significant for its definition of cultural significance and the standards it outlines for using cultural significance to manage and conserve cultural sites
European Landscape Convention	2000	An international treaty devoted to all aspects of European landscapes, including natural and human altered areas. The convention is aimed at raising awareness of the value of living landscapes as well as the protection and management of landscapes.

Matero (2006) summarises the principles within these documents as a series of professional/ethical obligations. The obligation to:

- Perform research and documentation; record physical, archival, and other evidence before and after any intervention; generate and safeguard the knowledge of structures and sites and their associated human behaviour.
- Respect cumulative age-value; acknowledge the site or work as a cumulative physical record of human activity embodying cultural beliefs, values, materials, and techniques while displaying the passage of time through weathering.
- Safeguard authenticity, an elusive quality associated with the genuine materiality of a thing or place as a way of validating and ensuring authorship or witness of a time and place.
- Perform minimum reintegration and re-establish structural and visual legibility and meaning with the least physical interference.
- Perform interventions that will allow other options and further treatment in the future. This principle recently has been redefined more accurately as 're-treatability', a concept of considerable significance for architecture, monuments and archaeological sites given their need for long-term high-performance solutions, often structural in nature.

While these principles guide ethical practice, at times they can be at odds with one another and complicated by conflicting stakeholder values. With earthen architecture, for example, methods of reconstruction or reburial are the most practical solutions, yet authenticity and access are then challenged. While there have been many positive effects from the all-encompassing nature of all these principles, their overly holistic nature can, at times, create grey areas of decision-making priorities.

3.6 Approaches to mudbrick conservation

The fragile composition of earthen architecture sites presents many challenges for conservators. In the case of archaeological structures, immediately after excavation, surfaces are exposed to environmental agents and temperature fluctuations that change the equilibrium achieved with internment, leading to structural instability and other micro-scale pathologies, such as cracking, material loss and surface delamination (Matero 2015). On the other hand, inhabited earthen structures are made habitable by the existence of foundations and roofs, functioning drainage systems and the maintenance or reapplication of protective renders (Oliver 2008). Due to its complex nature, the study of earthen architecture has mainly focused on the analysis of material composition, evaluation of different conservation methods (Cancino 2008; Friesem et al. 2011) and environmental stability. Above-ground ruins and excavated sites are subject to the impacts of temperature, wind, and moisture (in the form of humidity, precipitation and groundwater) and to the less foreseeable but often more catastrophic impacts of vibration and seismic activity, vandalism, lightning, animal activity and plant growth (Oliver 2008). Many studies have identified water and moisture as primary agents of deterioration as they promote the formation of soluble salts inside the mudbricks, which are subject to a cyclic process of dissolving and recrystallization that induces stress and loss of cohesion in the materials (Uviña Contreras 1998; Rainer 2008).

Archaeological sites are uninhabitable: roofs may be missing or only partially in place, foundations and drainage systems may be destroyed, walls may no longer be standing and much of the original structure may be buried. To complicate the issue, repair and maintenance strategies applied to inhabited earthen structures are often deemed inappropriate for archaeological sites (Oliver 2008). At archaeological sites with earthen architecture, significant damage to earthen wall surfaces has been observed immediately after or within a few days of excavation due to the rapid desiccation of features (Matero and Moss 2004). It is essential to prepare for and establish in-situ protective systems that allow earthen structures to gradually reach a state of equilibrium with ambient conditions, in conjunction with a monitoring program, to understand both the local environmental conditions and the presence of moisture in the walls and ground (ibid). Conservation interventions for earthen architecture generally include wall caps, temporary and permanent shelters, environmental stabilization, removal/relocation, reassembly/reconstruction and reburial. Other interventions comprise structural and seismic stabilization, drainage modifications, biological control and the use of consolidants, water repellents and modified earthen materials for repair (Oliver 2008).

Monitoring of large-scale heritage can be challenging. Survey methods are very often qualitative and subject to team continuity and expertise. Quantitative methods in monitoring are growing due to the prevalence of accessible technology. Three-dimensional (3D) documentation has become a common method in archaeological practice, implemented during excavations for in-field documentation but also for mapping purposes and damage assessment (Bornaz et al. 2007; De Reu et al. 2014; Lezzerini et al. 2016). 3D modelling is also useful for assessing damage at endangered archaeological landscapes and sites (Landeschi et al. 2016; Savage et al. 2017). It has been more recently applied to the monitoring of ancient earthen architecture (Fujii et al. 2009; Barnard et al. 2016; Campiani et al. 2019).

3.6.1 Conservation methodologies

Reasons for conservation interventions on earthen architecture include but are not limited to: loss of cohesion of the surface and/or joining interfaces, loss of stability of the wall (typically at the base), seismic activity, and deterioration due to internal or external factors (roof collapse, rain, salts). There are many conservation treatment options including preventive measures during excavation (wall caps, temporary and permanent shelters), reconstruction, reburial, and removal and relocation (Pedeli and Pulga 2014). Other common interventions incorporate structural and seismic stabilization, drainage modification, biological control, and the use of consolidants, water repellents and modified earthen materials for repair (Rainer 2008). There is also the controversial decision not to intervene at a site altogether (Emerson and Woods 1990).

The literature shows the varying approaches to the conservation of earthen architecture, moving through the degrees of intervention, from preventative conservation measures through to reconstruction. The literature on preventive measures taken for the conservation of architectural materials during excavation mostly pertains to stone, brick or mosaics, which are relatively stable compared to earth. Interventions are primarily confined to the instances of the installation of shelters, backfill during or between excavation seasons, or only over the excavation period (Alva Balderrama and Chiari 1987; Castellanos and Hoyle 2000; Stanley-Price 1984; Roby 1995; Çamurcuoglu et al. 2015). Generally, little is written on preventative measures for earthen architecture, which is much more vulnerable to the rapid environmental changes brought about during excavation (Matero and Moss 2004; Oliver 2008).

Maintenance is a crucial, but often forgotten aspect of preserving earthen heritage. Earth is not a static material and, irrespective of conservation treatment (i.e. polymerization), cannot be treated as such. As part of all archaeological site on display in-situ, the importance of designing, implementing and periodically evaluating a comprehensive site maintenance plan cannot be overemphasized (Rainer 2008). Maintenance plans are discussed in the literature (Crosby 1983; Brown et al. 1990; Gamboa Carrera 1993) but, again, site-specific case studies are needed that include environmental data. Most archaeologists, conservators and site managers are aware of the importance of maintenance, but more distant managers and funding agencies usually are not. Well-documented studies that stress the economic advantages of maintenance, in comparison to the more common treat-and-abandon approach, could help bolster arguments for increased legislative and financial support (Oliver 2008).

3.6.2 Cross-site interventions

Some large-scale interventions impact an entire site. Shelter construction, either temporary or permanent, at archaeological sites placed most often to protect ongoing excavations and excavators, is the most prominent example. There is a great deal of literature on archaeological shelters but is often irrespective of site typology (Gollmann 1987; Balderrama and Chiari 1995; Demas 2002; Pedeli and Pulga 2014). Shelter construction for both the covered and uncovered areas is often a complex issue with a myriad of factors impacting the decision to erect one or not. Shelter construction can create changes around the in-situ structures altering moisture levels, whether surface water, groundwater, humidity, temperature, wind speed and direction, and drainage. The insertion of heavy anchoring systems into cultural deposits is also a major consideration. The use of the shelter for excavators, the level of visitation and the degree to which the shelter must facilitate interpretation or separate visitors from the site must be considered. Also, the aesthetic impact of the shelter on the site and the landscape in addition to costs associated with construction and maintenance is also a factor in the decision (Oliver 2008). However, there is almost no quantitative, scientific research reported on environmental and condition monitoring before and after shelter construction to confirm observations that it was either protecting the site or causing increased deterioration (ibid). Published evaluations of existing shelters are primarily confined to empiric observations, though often there is little question that the shelter has reduced the rate of deterioration. But this cannot be quantified without data monitoring conducted before and after shelter construction (Bahn et al. 1995; de la Torre

1997; Mazar 1999; Matero 2000). With the growing application of terrestrial laser scanning, greater strides in quantitative monitoring for earthen sites, treatments and, by extension, shelter performance are now being achieved (Barton 2009; Fuji et al. 2009; Campanaro et al. 2016; Lingle et al. 2018).

Backfilling and reburial, the purpose of which is to stabilize the environment around the in-situ archaeology, are recognized as potentially effective methods of preserving archaeological sites (Agnew 2006). While backfilling and burial may provide the optimum environment for long-term preservation, guidelines and characterization of that environment have not been established (Nordby et al. 1988; Podany et al. 1994). Oliver (2008) points out there are, however, several unanswered research questions regarding appropriate backfill methods for a site. Much like with shelter construction, there is a need for extensive monitoring of the pre- and post-burial environment and quantifying the effects of different backfilling materials and designs on the archaeological remains and their effectiveness at stabilizing the environment (ibid). Questions relating to: how significant is the use of different types of fill or different types of geotextile need to be studied? Is it essential to use fill similar in composition and permeability to the natural fill at the site? What is the impact of alterations in soil pH? Would this be selected as a direct function of the amount of water present? At what depth and at what rate is equilibrium achieved? Alternatively, is equilibrium achieved? Does the use of a less permeable layer on the top of the fill reduce the amount of surface water infiltration, or does it prevent the evaporation of groundwater? What is the best way to protect from later biological growth? This myriad of questions must be researched before an evidence-based methodology can be used to apply backfill techniques.

The installation of wall caps is another common conservation intervention, in which unprotected tops of walls at excavated sites or standing ruins are covered with newly fabricated bricks. The purpose of the wall cap is to protect the top of the wall and vertical faces from erosion. Prefabricated blocks are installed on flat wall tops that often must be prepared by removing one or more courses of deteriorated original material (Hartzler and Oliver 2000). The permutations of capping materials, designs and intervention systems are endless, and the requirements of a particular wall can be site specific (ibid). The success of this type of intervention is limited to climate, as the deterioration would need to be predominately occurring at the top of the wall and not the base. Unsuccessful examples of this type of treatment have historically been done in concrete (Alva et al. 1980).

Alternatively, reconstruction, where entire sections are rebuilt, is a professionally divisive topic in conservation and its application to archaeological sites, especially of mudbrick, is not common today. Fragile and eroded earthen archaeological sites do not lend themselves to reassembly. In some instances, construction may be mechanically reattached or reassembled, varying in extent from the partial reconstruction, to additions such as buttress walls, means of directing visitor traffic, or elements to facilitate interpretation (Hartzler and Oliver 2000; Marchand 2000; Orazi 2000). Conversely, the removal of architectural elements from a site has been practiced long before the profession of archaeology. Earthen sites are more difficult to disassemble, and removal was primarily confined to unique or valuable elements, such as painted murals, reliefs and other decorative elements (Rainer 2008). With the growing recognition in the past century that much of the value of an architectural element is contextual, with improvements in preserving architectural elements in-situ, removal is less common today (ibid).

3.6.3 Localized interventions

Stabilization of the exposed walls and plaster/decorative surfaces can be restored for both aesthetic and structural purposes. Due to the diverse composition of materials used in earthen building materials and plasters, loss of cohesion and detachment of the plaster from its support are common problems. When the surface of a building material is at the point of deterioration, it needs to be either consolidated, reattached or removed to ensure the preservation of the surface or structure (Torraca 2009).

When deemed necessary and feasible, it is accepted practice to remove decorative walls/plasters via block-lifting. Once removed the feature usually receives further conservation intervention and then is stored off-site. Depending on what is being preserved, detachment can either occur strappo (surface only) or stacco (surface and underlying material) (Turton 1998). While this practice is professionally acceptable because it may save a decorative surface, it is problematic as it decontextualizes the object (Barry 2017). It is also obviously not a feasible method to treat an entire site.

Methods such as grouting and consolidation are common with a range of synthetic and natural materials. Mechanical reattachment of the plaster to the support can be achieved by anchoring or pinning, using iron or steel rods with metal or Plexiglas crosses to hold the plaster to the wall. However, these are rigid compared with the plaster material (Rainer 2008). Consolidation offers a way of strengthening the original earthen material without visually altering or inhibiting access, and thus is an ideal way to prolong the life of in-situ structures. The following provides an overview of research carried out discussing these interventions, with further information relating to polymer science in Chapter 4.

The grouting of cracks in earthen structures and their decorative layers has been researched and developed over the last twenty years. Treatments usually include liquid mortars with adhesive properties that are designed to fill gaps (Oliver 2008). It is preferable to use materials that are compatible with the original, both mechanically and aesthetically. Warren (1999) gives an overview of materials that can be used for grouting on earthen architecture. One of the most enduring treatments has been the use of low-alkaline hydraulic lime, liquid lime and PVAC (Schwartzbaum et al. 1986). Another method by Baradan (1990) uses a pozzolanic mixture of fly ash and lime.

Research carried out in the southwestern United States has looked at grouts for lime plasters on earthen architecture (Matero and Bass 1995). For areas with fine cracking, adhesives without other fillers or bulking agents are typically used. At Mesa Verde in 1981, a pilot treatment was carried out using a PVAC emulsion as an adhesive to reattach delaminated areas, notably after nine years, the treated areas remained stable (Silver et al. 1993). Similarly, in Jordan, archaeological remains were removed and remounted for museum exhibition; these remains were treated by injecting Paraloid B-72 (Lewin and Schwartzbaum 1985). Rainer (2008) notes that the use of such materials requires a contextual study for use in an uncontrolled environment with fluctuating conditions. Current trends focus on the use of compatible earth, with or without the addition of adhesives (ibid).

Consolidation studies in mudbrick have been carried out in different ways but have been met with mixed results. A variety of products have been tested and used in the conservation of earth including naturally occurring adhesives and mucilage, synthetic organic resins, and silicone esters and silanes, which act as binders (Oliver 2008). Stone consolidation processes have been widely used on earthen substrates since the start of the nineteenth century. The basic idea was that by the application of a single consolidation treatment, all conservation problems would be solved (Torraca 2009). As such, no maintenance was foreseen for the future, and it was assumed that the treatment would offer indefinite protection for the treated materials. Consequently, with these requirements, the conservation treatments 'failed,' along with some consolidation techniques that were actually efficient (ibid). When it comes to consolidation, no product satisfies all the criteria for an ideal consolidant, but the alkoxysilanes arguably come closest (Warren 1999; Chiari 2000). Alkoxysilane is a general term for silane solution that can penetrate porous building material and form a nonlinear glasslike matrix of silicon dioxide. Depending on chemical composition, alkoxysilanes may function as consolidants or water repellents. There are definite limits to their application. Alkoxysilanes cannot consolidate grains larger than coarse sand and need to be applied to both sides of a wall to avoid creating an adverse microclimate. It is also a costly treatment, as it needs to be maintained and reapplied - which is why there is still an investigation into other consolidation methodologies. The advantage of these consolidant systems is the low viscosity allows it to penetrate deep inside porous material, and polymerization occurs upon contact with environmental moisture; however, a negative characteristic of these materials is their tendency to form brittle gels susceptible to cracking (Mosquera et al. 2010).

There is a growing trend among earthen archaeological sites towards something that has been termed 'structural consolidation' (Fodde and Cooke 2013), whereby new earth materials are used and applied to ancient walls to provide structural stability and act as sacrificial layer from future weathering (Lingle 2014; Salmar and Togon 2016; O'Grady et al 2018). Stazi et al. (2016) extensively incorporates new earth in their study of different earthen plasters as protective measures to earth walls, and evaluates the effectiveness of the coatings in protecting the earthen walls against weathering. This methodology has been proven to be successful in extending the life of earthen structures and offers important opportunities for training and community engagement. Problematically, however, this treatment challenges ideas of authenticity and can be seen as restoration rather than conservation. There are those who are critical of this more reconstructive approach, citing the belief in the authenticity of historic and cultural resources as residing in the physical fabric, and especially for archaeological materials, traditional repair methods through substitution ‘in kind’ using the same or similar materials as unacceptable (Matero 2015).

3.6.4 Further consolidation research

When it comes to the consolidation of earthen substrates, Chiari (1990) offers real perspective to the discussion: ‘The idea of solving the problem of adobe preservation by coating the surface with some perfect consolidant should be dismissed. Each preservative shows advantages and disadvantages; the perfect treatment has not yet been discovered and probably never will be. Adobe is a weak material that has always been used with the idea of constant maintenance and repair. In most cases, the walls were originally protected by roofs, which in archaeological excavations are missing. One cannot expect to stop the natural evolution and modification of the material. All we can hope to do is to reduce the speed of deterioration.’ Thus, it is important to keep in context what is trying to be accomplished, there is no right answer, the important aspect is to truly understand what the materials being applied to the surfaces are achieving. One thing that needs greater sector emphasis is that, particularly with earthen architecture, all treatments can do is slow of deterioration and offer insight regarding the rate of change. The literature points to 'success' of a consolidation treatment as a complex function of the properties of the consolidant itself, due to clay mineralogy, and the degree to which the treated material can be separated from the causes of deterioration (Oliver 2008), however, there is limited information on what precisely measures success. This research aims to fill this gap in measuring consolidation success.

Given the need for a solution to the problem of deteriorating ancient earthen architecture and the commonality of consolidation practices on earthen architecture, this PhD research offers a way to contextually investigate historic conservation treatments to more clearly inform future interventions. With advances in analytical equipment, it is now professionally unacceptable to continue working in this area in an empirical and unsubstantiated manner. Chapter 4 highlights treatment reports that simply state that the material ‘appeared’ to be consolidation to a given depth, which does not adequately inform conservation practice. While qualitative assessments are part of sector practice, when it comes to treatment outcomes, there must be quantitative substantiation whenever possible. Consolidation is a prevalent conservation practice beyond earthen architecture. As technology develops and offers new avenues of understanding, it is an obligation within the sector to re-evaluate what is ‘known’. There is much to be gained from investigating historic treatment practices; for example, developing a sound understanding of what additives, like polymers, are achieving when applied in a specific context. The case study of the Neolithic site of Çatalhöyük, Turkey, provided in Chapter 5, demonstrates the value in looking at what was done to better understand impact and perception. Though consolidation is conceptually an ideal solution to aspects of earthen deterioration, is it the right line of research to pursue if the ideal is not achieved? To answer this question, a greater understanding of what is happening when consolidation takes place is necessary.

4 Consolidation of mudbrick

Consolidation acts at many levels, from the microscopic to the monumental

C.V. Horie 2010

4.1 Theory of consolidation

Consolidation, for the purposes of this study, refers to the process of applying a polymer system to an architectural earthen surface, with the aim of penetrating it to increase the strength and durability of the earth matrix beneath. Consolidants for earthen materials mentioned in conservation literature are grouped into three broad categories based on their chemical composition: inorganic (alkali silicates), natural organic (plant mucilage) and more commonly synthetic organic polymers (acrylic resins, vinyl acetate polymers, epoxy resins, polyurethanes, alkoxysilanes) (Oliver 2008). This PhD study focuses its experimental work on synthetic organic polymer dispersions, as they are commonly used in field conservation due to their ready availability and low cost. The study aims to gauge the commonly held perceptions of consolidation against experimentally derived evidence of treatment outcomes.

A consolidant inhibits the capacity for movement between microscopic particles, altering the behavioural characteristics of the material, particularly in the presence of water and making it stronger in compression and tension (Warren 1999). Consolidation has mechanical, chemical and optical effects, as the consolidant interacts with the material. The consolidant may simply bulk spaces or form secondary bonds according to the nature of both consolidant and substrate. Frequently its primary purpose is to increase the cohesive strength of the substrate, on a large or small scale (Horie 2010). Successful consolidation depends on placing and evenly distributing the consolidant where strengthening is required in order to reduce stresses at interfaces. In large scale architectural surfaces, this distribution uniformity is not easily achieved.

For consolidation systems that rely on evaporation of a liquid leaving polymer residues in the substrate, successful outcomes can be predicted based on a specific range of variables fulfilling several requirements, either independently or in an interrelatedly. These variables include substrate properties, polymer/liquid interactions, evaporation rates, ambient environment, viscosity and rheology considerations. In the case of large-scale heritage, the success of a treatment can be difficult to gauge. As the success of an intervention is not immediately apparent, an effective monitoring program is essential, supported by verification of treatment outcomes using laboratory research. This laboratory study focuses on exploring the outcomes of commonly used practices for consolidating mudbrick with dispersion and solvent polymer systems.

4.2 Selecting consolidants: solvent and colloidal (dispersion and emulsion) polymer systems

Selecting polymers to act as successful consolidants relies on understanding the chemical and physical properties of both polymer and substrate within its operational environment. While a polymer must successfully infuse the substrate to which it is applied, its mechanical properties will dictate its impact on the strength it imparts. Factors such as molecular weight, tensile strength, elasticity, transport, tack, glass transition temperature and mixing behaviour are all critical aspects of polymer performance. Long-term degradation of a polymer by environmental factors such as heat, light and chemicals will influence treatment choices, as they can change tensile strength, colour, shape and molecular weight (Favaro et al. 2006).

4.2.1 Solvent systems

Polymers that rely on evaporation of a liquid leaving behind polymer molecules to form a film can either be solvated as individual molecules or exist as dispersed particles, comprised of a large number of molecules, within a colloidal system (Lamprecht 1980). For solvation, a solvent will need to be attracted to the polymer molecules by secondary forces that include all or one of the following: Van der Waals forces, polarity and hydrogen bonding (Van Damm et al. 2010). Which forces act will be dictated by the chemistry of the polymer and solvents will be chosen accordingly. For organic polymers this means solvents are mostly organic molecules, chosen according to their solubility parameters, which must enable them to be attracted to individual molecules in the polymer to surround and solvate them (Lamprecht 1980). Surface tension effects from organic solvents are low and consequently these solvents will wet many surfaces effectively, which is an advantage for consolidating porous materials where polymer must be carried into a porous substrate. Evaporation will limit the wetting advantages of some commonly used organic solvents due their rapid evaporation rates (ibid). This will influence dwell time of the solvent in a substrate, which makes climate an important factor to consider in consolidation procedures. At Çatalhöyük the high summer temperatures and dry air will increase evaporation rates, effectively concentrating the solution and increasing its viscosity, which will reduce its ability to penetrate pores by decreasing solution mobility. Equally, back flow of polymer from the body of a substrate, due to its solvent feeding evaporation at the substrate surface, will be reduced by increasing viscosity. Health and safety restrictions are likely to apply with organic solvents, as rapid evaporation may raise the local concentration of solvent above acceptable Threshold Limit Values (TLV) for safe working with toxic organic solvents (Pascoe 1980).

There is also the factor of 'tack' to consider. Some polymers are 'tacky' when dissolved. Tack measures an adhesive's ability to adhere to a surface quickly. It is defined by the American Society for Testing and Materials (ASTM) as the ability of an adhesive to form a bond of measurable strength to another surface under conditions of low contact pressure and short contact time (ASTM 2017). Tacky polymers adhere quickly to fingers, are 'stringy' to the touch and form films quickly. As solutions evaporate, polymer viscosity increases and certain polymers will become very tacky, restricting their flow. Tacky polymers are anecdotally thought of in conservation as being good adhesives for holding things together, in this case particles within a porous substrate.

Cost is also a factor to consider for organic solvents, compared to water they are very expensive and often difficult to obtain in remote areas such as Çatalhöyük. Practical use of solvent systems is linked to using low concentrations of solution, as the viscosity of solutions increases significantly with increasing concentration. Comparing a 40% Paraloid B72 solution in acetone (viscosity 3000 mPa s) with a 36% solids Acrysol WS 24 dispersion (viscosity 600 mPa s) illustrates this property (Table 4.1). Typically, 5% w/v solution would be considered a maximum in many instances.

4.2.2 Dispersion System

Dispersion systems are in common use within conservation practice. Polymers that are incompatible with water are given compatibility by the use of additives and sometimes by modification of the polymer at the manufacturing stage (Bugada, and Rudin 1984). These additives modify the polymer by increasing absorption (surfactants), providing miscibility in water (emulsifiers), and improving wetting (wetting agents) within the water, which also contains thickening agents and buffers (McKeen 2006). They are formed from a dispersed phase (polymer) and a background or continuous phase (water), with the polymer formed into colloidal size particles (0.001 to 1 µ) (Lazzeri 2016). The particles or beads comprise many molecules surrounded by the additives that make it compatible with water. The particle bead can be liquid (emulsion) or solid (dispersion).

Dispersion systems have the advantage of being able to contain large amounts of polymer yet have low viscosity, as compared to organic solvent-based polymer solutions of the same concentration. Dispersions form polymer films by coalescence of the polymer beads when the water evaporates. This requires beads to be tacky and adhere to each other on impact, yet they must not adhere together within the liquid continuous phase. This is achieved by the particles having a similar charge, so they repel each other in the liquid phase but the charge attracts water molecules to produce compatibility with the water (Van Damm et al. 2010). Coalescence requires the particles to adhere to each other at low temperature, allowing them to form polymeric films in cool environments. The minimum film forming temperature (MFFT) records the lowest temperature at which this will occur and is typically less than 8^{o}C, which often requires the polymer to have lower glass transition temperatures (Tg) than solvent based polymers (Table 4.1). This means that set dispersion polymers are often above ambient temperature, increasing their softness and enabling creep or flow to occur at high temperatures. This can impact on strength characteristics for polymers acting as consolidants, yet it will also offer a degree of toughness to substrates according to the substrate composition. Given a low Tg, high temperatures can produce a tackiness in the dispersion polymer that will attract dirt. At Çatalhöyük this means that for a large portion of the year, Primal AC -33 and Primal B60A within mudbrick will be above their Tg (Table 4.1). Prevention of polymer coalescence that can occur when latent heat of evaporation from drying of polymer reduces local surface temperature below MFFT is not likely at Çatalhöyük, unless there was conservation work in the winter months.

The tendency of dispersions to yellow more than resin based solvent polymers, especially homopolymers, is not of importance for mudbrick, as it is not intended for there to be a surface film (Duffy 1989). Similarly, dispersions have increased ageing rates and routes due to their additives. This is of no concern for mudbrick, as many of the ageing initiations and accelerators, such as light, will not reach inside the mudbrick matrix. The advantage of low viscosity in dispersions is countered somewhat by the fact that water has a high surface tension and that the polymer exists as particles, overall these factors will produce less mobility of a consolidant in many instances. However, since the clay particles in mudbrick will be negatively charged, water will be attracted to them due to its polarity, enabling it to wet the mudbrick (Fernandes et al 2012). The size of the polymer particles means they must be applied in dilute solutions to achieve adequate depth of penetration, but they must also be applied in sufficient concentrations to ensure consolidation (Warren 1999).

4.2.3 Polymers commonly used in conservation practice on earthen architecture

Acrylic resins are commonly used as adhesives and consolidants for a variety of materials including earthen substrates. Those used for consolidation include Paraloid B-72 (copolymer of ethyl methacrylate and methyl acrylate), Paraloid B-67 (butyl methacrylate), and Paraloid B-48N (copolymer of methyl methacrylate and butyl acrylate) (Morales Gamarra 1983; Helmi 1990; Šramek and Losos 1990). Acrylic dispersions used as consolidants for earthen substrates include, primarily ethyl acrylate/methyl methacrylate copolymers (Primal AC-33/B60A, Rhoplex E-330, Acrysol WS-24) and are also used as additives to new earthen materials (Koob et al. 1990; Morales Gamarra 1983).

For this PhD study, Primal B60A was the main focus of the experimental study due to its application at Çatalhöyük. Other synthetic organic polymer systems also commonly used in field practice were tested as comparators (Koob et al. 1990; Cooke 2008). Both aqueous and non-aqueous systems were tested on analogue samples using the same surface application of polymer and with similar concentration values. See Table 4.1 for a list of polymers used and the rationale for choosing them. The term Rhoplex and Primal are used interchangeably in the literature as Rhoplex is the North American commercial name for the same product, which called Primal in the European market. This study uses the trade name Primal, specifically Primal AC-33 and Primal B60A (ethyl acrylate and methyl methacrylate copolymer).

Table 4.1 Polymers, media, and concentrations

Trade Name	Composition	Particle Size	Percent solids	Media	Concentration(s) Utilised in this study	Glass Transition Tg (°C)	pH	mfft (°C)	Viscosity mPa s	FTIR Peaks	Availability/ Cost 5ltr/5kilo Low=>£40 Med.=£40-70 High=<£70	Reference(s)
Primal AC-33 (Rhoplex AC-33)	methyl methacrylate, ethylacrylate, and ethyl methacrylate	0.1µm	46	Water	5% v/v	16	9.4 to 9.9	8	850, neat	(2980-2950), 1732	Discontinued	Matero 1995; Rico 2004
Primal B60A (Rhoplex B60A)	ethyl acrylate and methyl methacrylate copolymer	0.03µm	46.5	Water	5% v/v 10% v/v 25% v/v	22	9.4 to 9.9	9	1125, nest	(3005-2850), 1734	Internationally Available/ Low	Pye and Cleere 2009; Cooke 2008
Acrysol WS-24	acrylic colloidal dispersion in water	0.03µm	36	Water	10% v/v 20% v/v	46	7	-12	600, neat	(3000-2870), 1750	Internationally Available/ Low	Koob 1990; Kres and Lovell 1995
Paraloid B48N	methyl methacrylate and butyl acrylate	-	-	Acetone	5% w/v 10% w/v	50	-	-	3000 40% w/v in acetone at 25°C	(2950 2940), (1726-1718)	Limited International Availability/ Med	Helmi 1990; Šramek and Losos 1990
Paraloid B44	methyl methacrylate and ethyl acrylate	-	-	Acetone	5% w/v 10% w/v	60	-	-	460 40% w/v in acetone at 25°C	(2965-2850), 1740	Limited International Availability / Med	Lingle 2014; Peters et al. 2017
Paraloid B72	ethyl methacrylate and methyl acrylate	-	-	Acetone	5% w/v 10% w/v	40	-	-	200 40% w/v in acetone at 25°C	(3035-2820), 1720	Internationally Available/Med	Morales Gamarra 1985; Šrámek and Losos 1990
Water	H_2O	-	-	-	-	-	7	-	0.0091 at 25°C	-	Internationally Available/ Low	
Acetone	CH_3COCH_3	-	-	-	-	-	7	-	0.33 at 25°C	-	Internationally Available/ (variable) Low, but can require licencing to acquire	

4.3 Consolidating mudbrick

Challenges exist when consolidating mudbrick. Pores in earthen substrates are irregular and non-contiguous, and it is difficult to obtain accurate porosity measurements, as the absorbent nature of clay and the lack of a water-resistant binder, make many standard porosity tests uninformative. The success of aqueous systems at the application state of consolidation, is inherently difficult to judge in mudbrick because of the relationship between clay and water. Clays both adsorb and absorb water; this wetting process can give the appearance that a mudbrick has been well consolidated, but this offers no evidence of how far the aqueous polymer system has moved through the material. In archaeological contexts, it becomes even more complicated with walls that are only partially exposed.

In 1990, the 6th International Conference on the Conservation of Earthen Architecture addressed a variety of subjects, including studies in consolidation (GCI 1990). Since then there have been various other publications of earthen sites incorporating consolidation programs, but they provide little information as to how the depth of penetration tests were carried out or rely on mere visual examination (Oliver and Hartzler 2000; Ferron and Matero 2011). Methodologies for assessing penetration tests include spectroscopy, X-ray radiography and tomography, dye systems, firing tests, scanning electron microscope (SEM) (Ling 2010; Conti et al. 2011; Heo et al. 2011; Slavíková et al. 2012). Many of these systems, however, would be unsuitable for analysing either mudbrick or aqueous polymer consolidation systems; additionally, tests often lack real-world application and do not reflect field practice, which is why studies, like this one, that incorporate laboratory analysis and link it back to conservation interventions actualized in the field are needed.

4.3.1 Related studies

Most studies in the literature report either that acrylics, as dispersions or solutions, were ineffective consolidants, or that alkoxysilanes were more effective (Oliver 2008). Alkoxysilanes carry the concept that compatible materials are being applied to the earthen substrate. The major difference between alkoxysilanes and organic polymers such as acrylics and polyvinyl acetates is increased toughness and adhesion of the organic polymers. The physical and mechanical properties of acrylics are different to those of earthen materials, and acrylic polymers must be applied in sufficiently low concentrations to limit changes in the properties of the original materials that impact on physical properties and/or ethical contexts. These include colour, reflectance, vapour permeability, and thermal properties. There are reports of successful consolidation and some depth of penetration of an acrylic polymer (at least 7 cm) using 5% w/v solution in xylene (Šramek and Losos 1990; Matero and Moss 2004). It is important to note, however, the health hazards, cost and limited availability of xylene make it an impractical choice for use in the field. Further research and manipulation of acrylic systems may result in good consolidants that are stronger than alkoxysilanes (Oliver 2008). An overview of polymers and analysis in relevant consolidation studies are offered in sections 4.3.2 through 4.3.4.

While there are few all-encompassing case studies, two bodies of work are particularly important: most notably the conservation research undertaken at Fort Selden, New Mexico, and the other at Mesa Verde, Colorado. The Fort Selden project was notable for its experimental design in the field and the length of the project, 1985-2001. Whereas, the Mesa Verde project aimed to develop a comprehensive management system for the remedial and preventive conservation of earthen structures. There is no question that both projects were significant advances in the field of conservation of earthen architecture; however, there were limitations with how the consolidation work was analysed. As a result, there are analytical short comings in these significant pieces of research.

4.3.2 Fort Selden

Fort Selden was one of several adobe forts built by the United States Army to protect settlers, travellers, and traders in the southern part of the Territory of New Mexico in the 19th century. Today, all that remains are the sections of adobe walls and the stone walls of the prison. The Getty Conservation Institute, in collaboration with the Museum of New Mexico State Monuments, conducted a long-term research project on adobe consolidation at historic Fort Selden. In response to the ongoing deterioration of the adobe walls at Ft. Selden and at other sites both historic and modern in the southwestern United States, the Adobe Test Wall Project was developed (Selwitz and Oliver 2002). In 1985, a total of fifteen walls were constructed for the Adobe Test Wall Project–Phase I to test a wide range of protective coatings, wall caps, and wall foundation treatments (Taylor 1990). In total, there were three phases of the project to examine the long-term treatment effects Selection of the preservation techniques and materials for testing was made after a literature review and consultations with professionals in the adobe construction and preservation fields, once testing began the test walls were regularly monitored and photographed through 1991 in order to document their performance over time (Oliver 2000).

This project was a significant step forward in assessing the long-term outcomes of conservation interventions and the effectiveness of treatments. Too often within the profession, solutions are devised and materials used without post treatment assessment (or go unpublished because they were unsuccessful). Understanding of what conservation is achieving in practice, rather than in theory or intention, is gained from quantitative treatments with an analytical assessment of outcomes; few such studies exist in the conservation literature. For the project, a series of walls were built for testing preservation strategies. For the consolidation portion of the project, the best long-term performance was with a multi-step process using alkoxysilanes. Several factors limit the treatment to this particular site:

- the walls are freestanding thus, treatments can be carried out on both faces of the wall – there are limited opportunities for this when treating archaeological remains, as often not all faces of the walls are excavated;
- there was some environmental monitoring, and while that is less of an issue as the project spanned several decades, more significant inferences are needed between the treatments and the climate;
- most relevant to this PhD study, Koob et al. (1990) discusses depth of penetration on separate mudbricks in an entirely observational matter without actually investigating the behaviour of the polymer: 'In order to assess the penetration of the consolidant, the brick was broken in half after forty-eight hours when it felt dry to the touch. It was easy to see where the consolidant had penetrated because it had slightly darkened the substrate and had not completely dried in the centre.'

Relying on visual examination is arguably inadequate and does not provide any useful insight into what the consolidant was achieving. While there was a great deal of useful information gathered during this study, most of it can be classed as qualitative. The study, though long-lived, was a product of its time and did not have the types of analytical resources available today. The quality of the data could be exponentially increased by adding processes like 3D modelling, consolidation mapping, compression testing, and better environmental data.

4.3.3 Mesa Verde

Mesa Verde National Park is a World Cultural Heritage Site and one of the largest archaeological preserves in the USA, with over 4,000 archaeological sites, most iconically 13th century cliff dwellings. In 1994, the National Park and the Architectural Conservation Laboratory of the University of Pennsylvania collaborated on developing a comprehensive management system for the remedial and preventive conservation of earthen resources and integrating simple preventive conservation practices into park maintenance in order to prevent further loss and damage of the archaeological record. Several projects were undertaken to meet this aim, most pertinent to this PhD was the consolidation work by Ferron and Matero (2008).

For the experiments, facsimile coupons representing earthen finishes found at Mesa Verde National Park in Colorado were used to measure exposure to changing relative humidity, response to liquid water, surface cohesion, and effect on appearance (ibid). The use of coupons rather than blocks is somewhat problematic for this study, as thin samples of clay materials perform differently to thicker sections. Analytical methods included: measurement with linear variable differential transformer, environmental scanning electron microscopy, time-lapse photomicrography, observation during wet-dry cycling, water drop absorption testing, colourimetry, and photographic recording (ibid). Through the intervention options discussed for the disaggregating earthen finishes at Mesa Verde National Park, treatment with ethyl silicate consolidants was found to be the most robust. The tests, however, left out environmental modelling and depth of penetration analysis of the consolidant. These factors are crucial for determining the effectiveness of the treatment and limit the value of the study. Additionally, increases in durability and strength are factors that are essential for determining the merit of an intervention.

4.3.4 Consolidation penetration and performance studies

Part of the proceedings of the 1990 Terra conference or The 6th international Conference on the Conservation of Earthen Architecture, 'Adobe 90' was dedicated to consolidation studies. Here a mix of field experiments and laboratory experiments discuss 'successful' consolidation treatment outcomes, chiefly of silane systems. These systems offer promise but suffer from health and safety issues due to their potential impact on the human respiratory system (Koblischek 1996), and solvent volatility in high heat. Depth of penetration was examined by a range of methods including, chiefly observational monitoring, but also moisture loss on excursion, and scanning electron microscope (SEM) mapping (Agnew 1990; Coffman et al. 1990; Helmi 1990). Though most of these studies ultimately rely on disaggregation (via soaking in water) to access consolidant penetration (Chiari 1990; Coffman et al. 1990), as organic polymers cannot be reliably detected in an earthen substrate due to the overlapping of elements such as oxygen, hydrogen, carbon, and silica. Performance testing was done by compression testing of impregnated analogue adobe plugs (Coffman et al. 1990). Also discussed is the application of soil slurries or renders mixed with polymers acting as a sacrificial surface to the mudbrick (Agnew 1990; Fern 1990). Koob et al. (1990) discuss the use of acrylic colloidal dispersion (Acrysol WS-24), but again the study relies on empirical information to assess the depth of penetration. One of the most significant issues with these early consolidation studies is that when it comes to depth of penetration, there is almost no quantitative analysis, at the same time; however, there is no professional impetus to revisit these studies and reanalyse them in a more scientifically sound manner.

Chiari (1990) discusses synthetic resins (long chains of organic polymers derived from a vast range of monomers), most commonly used are polyvinyl acetates, acrylics, and polyisocyanates. Abstractly speaking, as consolidants for earthen architecture, they are fit for purpose - they can be used in solution in organic solvents, in water emulsions, or the polymerization through reaction with atmospheric moisture. In the case of emulsions, the polymer globules suspended in water are relatively large, the liquid has a high viscosity, and penetration is low (ibid). Water is not a suitable carrier in the case of adobe since it causes swelling of the clay particles and decreases the mechanical properties with the risk of material detachment during the treatment. It is Chiari's opinion that emulsions should, therefore, be applied as adhesives only, by injection inside the walls, and never on the surface.

Both water and solvent-based polymer systems have been applied to earthen architecture. There has been widespread use of PVAC in water, both on fragments in a museum environment and in-situ (Miller et al. 1987; Lewin and Schwartzbaum 1985). Additionally, other case studies report using PVAC in various solvents: PVAC in toluene and loose pigments that have been fixed with a dilute solution of PVAC dissolved in toluene, alcohol, and ethylene dichloride (Sengupta 1984; Singh and Sharma 1993). For flake laying and similar superficial treatments on earth acrylic dispersions and emulsions in water have also been used, including Primal AC-33 (Silver 1997; Piqu and Rainer 1999). In the tomb of Nefertari, for example, conservators used Primal AC-33 (30% in water) to reattach paint flakes to the earth plaster (Mora and Mora 1993). Another synthetic adhesive that has been used widely in wall painting conservation is Paraloid B-72 in various solvents.

Few long-term evaluations of adhesives are evident in the literature; the exceptions are large scale projects at Mesa Verde and Fort Selden, in which prior treatments were evaluated (Oliver 2008). Beyond consolidation, there is a need in the conservation of earthen architecture for greater publication of monitoring and evaluation of the performance of past interventions, at both the site-specific and comparative levels (Chiari et al. 2000). Greater research into the performance of interventions in specific site climates is also much needed (Rainer 2008).

4.3.5 Archaeological context

In archaeological field practice historically, aqueous polymer systems are common choices due to their availability and low toxicity (Cooke 2008). With aqueous polymer systems, visual examination of earthen materials consolidation can be misleading as water mixed with the polymer separates and seeps into the substrate, giving the appearance that consolidation is taking place when it is not. Research carried out by Koob (1988), and Torraca (1990) suggests that the viscosity of acrylic emulsions is too high for successful penetration of earthen substrates. However, the consolidant was considered to be part of an effective treatment regime at sites like Çatalhöyük (Pye and Cleere 2008; Cooke 2008).

Several case studies mention the use of Paraloid B-72 (Acraloid B72) (ethyl methacrylate (70%) and methyl acrylate (30%) copolymer soluble in several organic solvents) for earthen surface consolidation (Rainer 2008). Paraloid B72 is a recognised go-to polymer in conservation as a consolidant, an adhesive and a coating with many studies on its intrinsic properties and some on its performance (Morales Gamarra 1985; Koob 1986; Šrámek and Losos 1990; Matero and Bass 1994; Yang et al. 2007). These have produced various and inconclusive outcomes that are not quantitative. Paraloid B-72 used as a consolidant at the Dambulla Temple Complex in Sri Lanka; areas of powdering paint on earthen polychrome bas-reliefs were consolidated using 3%–5% Paraloid B-72 in acetone in localized areas (Bandaranayake 1997; Piqu and Rainer 1999). In the tomb of Nefertari, where the original binding medium had disintegrated, causing the paint to become powdery over much of the painted surface, the wall paintings were treated with 3%–5% Paraloid B-72 in lacquer thinner (Mora and Mora 1993).

In China, there are many relevant publications which have been released regarding the consolidation of earthen substrates; unfortunately, few of them undergo translation (Xu 1991; Xie 1997; Li et al. 1993; Yang 1996). Su and Li carried out experiments using colour monitoring instruments to measure the colour change of specimens before and after PVAC, PVOH, and Paraloid B-72 were applied. Results showed that Paraloid B-72 causes more colour alteration than PVAC and PVOH (Su and Li 1996). These studies are more focused on specific aspects of treatment on earthen decorated surfaces, rather than holistically treating earthen walls. While colour is an important aesthetic this must be balanced against the primary goal of any consolidation, which is longevity and strength, they should not create bias before holistically assessing a problem.

More recently, Ren and Kagi (2014) used dye taggers and wetting/drying cycles to look at the efficacy of soluble sodium silicate on mudbricks following impregnation. Wang et al. (2016) examine consolidation effects at the Liangzhu site in China, using thermo-physical parameters testing, infrared thermal imaging, high-density microelectrode resistivity testing, portable microscope observation, and hydrophilic and hydrophobic testing, all of which are carried out in the field. Logically, the penetration depth of consolidants applied to cultural heritage objects plays a crucial role in successful conservation and protection of them. Ropret (2017) designed a project examining the depth of penetration of modified tetraethoxysilane-based consolidants for silicate-based substrates Raman and (FTIR) spectroscopies. The study sites both the success of FTIR spectroscopy for consolidation mapping over Raman and more precise penetration depth estimation than visual assessment alone (ibid). It is auspicious to see parallel work to the analysis carried out for this PhD, corroborating the validity of part of the methodology, though their study examined silanes on sandstone in laboratory conditions.

4.4 Impact of consolidation in the field

The methodologies for determining consolidation treatment outcomes such as hardness, depth of penetration, and coherence have evidence limitations in the field. For practical purposes, laboratory testing relies on samples or fabricated facsimiles; however, there are too many variables for large scale in-situ architecture for these tests to be directly correlative. There is a limited expectation, however, that a consolidant will perform similarly in both a laboratory as in the field, facilitating projection to in-situ contexts. This predictive approach can be improved by identifying how laboratory variables may differ in a field context and seeking to make allowances for these. While laboratory testing can rely on evidence derived from quantitative analysis, assessments in the field are typically subjectively assessed, either immediately or in the long-term by looking at qualitative elements such as: colour change, reduced erosion rates, uniformity in erosion patterns, pitting, and visual indication of depth of penetration (Oliver 2000).

The types of polymers and solvents suited for laboratory testing are not necessarily reflective of what can be applied in the field. Availability can dictate the use of polymers and solvents, making effective treatments impractical to use. Another key factor is the volatility and toxicity of the solvents. Climate can have an impact here speeding up or slowing down solvent evaporation, which can impact on factors such as the chromatographic back movement of polymer and penetration depth, rendering polymers and solvents effective in ambient laboratory conditions unusable. More toxic solvents are difficult to manage in the field – heat is often a factor, but also access to personal protective equipment (P.P.E.) and whether is it feasible to wear the necessary P.P.E. while working on site. An additional issue with field application can be contamination, as it is much more difficult to access and control solution purity while in the field.

A study by Coffman et al. (1990) shows that one of the problems encountered after the application of consolidant to earthen substrates is the formation of a consolidant-rich outer film on the face of adobe masonry. Film formation may cause accelerated deterioration of the adobe by inducing separation of the treated outer layer from the untreated inner core (Illampas et al. 2011), this phenomena will be discussed further in Chapter 5. Additionally, consolidation may be ineffective or even produce adverse results when applied on walls, the bases of which are not protected from rising damp (Chiari 1990).

4.5 PhD context and overview

The aims of the experimental work carried out with this PhD research are to examine the efficacy of consolidation in the field and highlight what conservators have to consider before and after a treatment is carried out. A combination of laboratory techniques form an investigative methodology for elucidating the outcomes of current and historic conservation interventions on earthen architecture, with a focus on procedures carried out at Çatalhöyük, by examining polymer penetration depth and its impact on substrate strength. This chapter has identified the abundance of empirical evidence on consolidation performance within earthen architecture. This PhD seeks to scale an analytical methodology, then use it reproducibly to investigate commonly used field procedures for consolidating mudbrick, thereby contributing to better interpretation of the commonly held beliefs that surround the use of consolidation in practice.

5 Çatalhöyük Turkey: Case history of field conservation

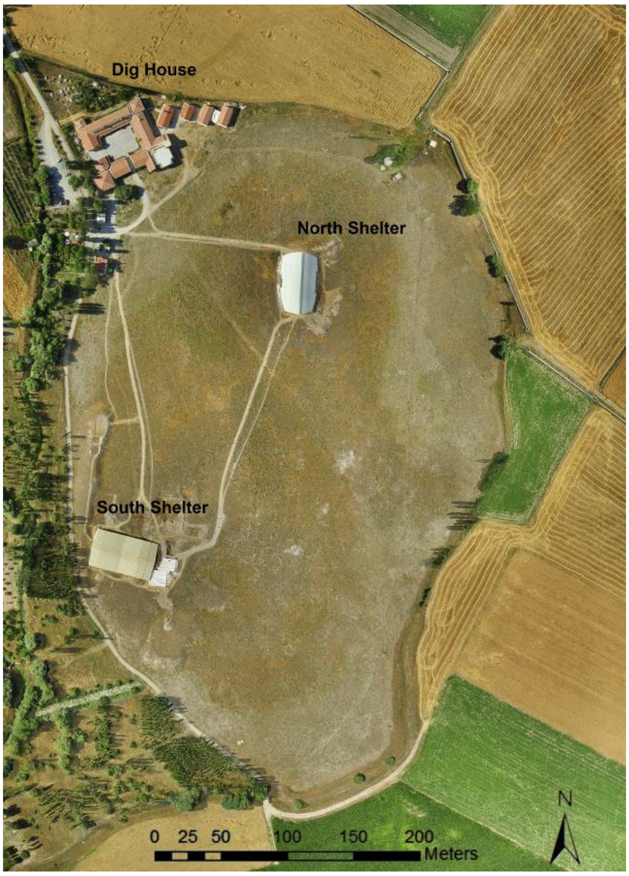


Figure 5.1 Drone SFM-generated Orthophoto of the Çatalhöyük East Mound in July 2015 (Captured by N. Lercari 2015).

5.1 Introduction to the site

Çatalhöyük is a proto-city dated to 7100-5950 BCE near Konya in central Turkey. The site is a Neolithic mound or hoyük and one of the largest ancient towns in the country (Figure 5.1). The Konya plain, an agricultural landscape on the southern edge of the Anatolian Plateau, has a flat and almost treeless topography. The name Çatal means fork in Turkish, as the site was once divided by a river. This location made the site ideal in terms of easy access to water, fertile land, and building materials such as clays and timbers. There are two mounds, the main East Mound (Neolithic, approx. 7100-5950 BCE) and later West Mound (Chalcolithic, approx. 6000-5500 BCE) (Göktürk et al. 2002; Human 2012). The site covers 37 hectares and is 21m in height from the plain at its apex, having 18 layers of occupation (Human 2012). Before the excavations at Çatalhöyük in the early 1960s, there was little evidence to suggest early development of agriculture and towns outside the Fertile Crescent, the so-called 'cradle of civilization' spanning what is now Iraq, Egypt, and south-eastern Turkey. Though Çatalhoyük was neither the earliest nor largest farming community in Anatolia, it was a significant participant in the cultural and economic changes that swept across the Near East in the Neolithic Period (c. 8,000 – 5,500 BCE) (Hodder 2006). As conservation research has focused on the Neolithic East Mound, the following overview will focus on the Neolithic half rather than the whole of the site.

Its strategic location in Anatolia means Çatalhöyük was in a vital position during the spread of the Neolithic way of life to Europe and beyond (Human 2012). The site is notable for its large size, with an estimated population of 3,000 - 8,000 people, and the duration of its occupation which was over 2,000 years (ibid). In addition to the Neolithic mound, there are other cultural deposits at the site including late Bronze Age, Hellenistic, Roman, Byzantine, early Selçuk burials and rubbish pits. There have been various phases of excavation at the site since the 1960s, initially by James Mellaart and later by Ian Hodder from 1993. Over the years, Çatalhöyük has grown in international stature and was inscribed on the UNESCO World Heritage List in 2012, which has led to a greater emphasis on the long-term preservation of the site (Lingle and Lercari 2017).

Çatalhöyük is one of the best examples of the agglomeration of people into egalitarian society in the Neolithic owing to its large size, continuity of occupation through time, the dense concentration of material culture, and a remarkable level of preservation (Human 2012). There are two main excavation areas on the East mound with permanent shelters (North Area and South Area) and smaller auxiliary trenches on the south of the mound (TP, TCP, GDN, IST). Since the site's discovery in the 1950s, approximately 200 buildings have been excavated at Çatalhöyük East, which constitutes less than six percent of the mound, as part of the conservation management (SMP 2004). Buildings are excavated using a single context methodology, with the phases of occupation grouped temporally. Neighbouring buildings are grouped into levels, allowing for the reconstruction of contemporary neighbourhoods.

Excavations reveal that the main architectural components of the East Mound site are densely clustered houses, with open areas of communal or midden (refuse) deposits between them (Human 2012). The buildings were thoroughly cleaned, and most portable artefacts removed before abandonment in antiquity, as such external spaces are vital in examining specialized production of goods. On both mounds, houses are clustered together without streets and with roof access. In antiquity, as the need arose, new houses were built on top of the old, initiating a new phase of buildings in the settlement. The excavations indicate little evidence for large public buildings, ceremonial centres, or cemeteries. There is extensive art, symbolism, and burial occurring within houses with the division of buildings into 'shrines' and 'houses' being unclear and continually debated (Hodder 2010). The current evidence indicates that society at Çatalhöyük was egalitarian without large-scale centralized administration; even art seems to have been produced in a domestic context (ibid).

5.2 Architecture

The Çatalhöyük settlement is composed of mudbrick houses densely packed together. All walls are constructed of unbaked mudbrick, usually of large dimensions, ranging from 10cm to over one meter in length and height (Figure 5.2). Generally, every building had its own four walls, although during the early sequences there was more use of shared walls between buildings. There are almost no exact right angles, and the feeling is of an organic, cellular agglomeration of buildings (Love 2013). As houses were only separated by centimetres, there was no ground-level access point and no streets or alleyways between the houses. Subsequently, it is interpreted that access was through a hole in the roof and a ladder (Hodder 2010). Activities took place inside the buildings as well, despite the apparent poor light and ventilation owing to the absence of window openings (Ibid).

Internal spaces were covered in layers of white plaster, typically composed of thin marl (clay) layers but, in some instances, with lime also incorporated into the surface coatings (Matthews 2005). Analysis of different areas within the houses revealed differences between the nature of sources, preparation, how, and where were plasters were applied (Tung 2005). In the southern ends of the buildings, smaller rooms where cooking activities took place generally have thicker and coarser plasters, while more extensive and more elaborate spaces (with platforms, benches, installations, and paintings) in northern parts of the building were plastered with fine white marl (Matthews 2005).

North Area 2017

South Area 2017

Figure 5.2 North and South Area open display buildings of Çatalhöyük (Photographed in 2017 by the author).

The internal plan of the houses was generally the same across the site and throughout its occupation. Buildings appear to consist of one large room, often approximately square in plan, with or without additional smaller rooms, and discrete house units are well-defined (SMP 2013). There were wooden support posts set in large pits against the internal walls. Roofs were made of oak and juniper crossbeams that supported clay and reed surfaces (Human 2012). Inhabitants slept, ate and made food and tools in these houses which contained ovens and hearths, art and ritual and burial spaces. There was often also a side room which was used for storage and food preparation. Earth and plaster platforms found in some of the large rooms were possibly used for sleeping upon (Hodder 2010). A large clay oven, with a small circular hearth for cooking nearby, was generally positioned against the south wall, over which the access hole and ladder from the roof was located (Ibid).

There is little archaeological knowledge of the roofs, as these are removed during the deposition in antiquity. The house 'furnishings' often included a single or group of storage bins and shallow basins in the side room (ibid). Changes and small variations in the layout of the interior features took place during the life of the buildings. New ovens and hearths were built, and storage bins and basins were added or removed (SMP 2013). Frequent use was made of white clay-based wall plaster, with multiple applications visible in most cases. The internal walls of the house, niches, the posts, and the 'furniture' were plastered in white lime-based clay and re-plastered periodically; it was these plastered walls surfaces that were sometimes elaborated with paintings and three-dimensional mouldings (ibid).

Houses were occupied for about 30 to 80 years, after which the house was generally emptied of portable items and carefully and systematically dismantled (Hodder 2010). While some houses had short lives, others have evidence of being rebuilt several times. Often these longer-lasting houses had more burials and were the more elaborate in terms of art and internal architectural fittings; there is also evidence that some of the internal symbolic features were reused from earlier houses (Human 2012). Floor areas across the building, basins, and storage bins were usually cleaned and contents removed. Crawl-holes and niches were carefully blocked up to take the weight of the new wall. The oven was preserved by careful infilling; otherwise, they were partially demolished (ibid). The roof was then dismantled; first, the roof beams were removed, and finally compacting soil into the emptied structure. The roof posts arranged against the internal walls were 'dug' out with retrieval pits and associated post scars being found in the plaster of the walls. Walls were then dismantled in a controlled way, course by course (ibid). The mudbrick and mortar debris were crushed and used to fill the old building, which made a consolidated foundation for the new building. Only when the infill had reached, the top where the walls for the new house built, mostly directly on top of the walls of the old house (Hodder 2010).

5.3 Features currently on-display

When Ian Hodder took on the direction of the site in 1993, one of the principal aims of the project was the inclusion of conservation within the archaeological program. To facilitate the site becoming a place of cultural tourism, conservation measures were sought for open display of the in-situ structures on both short- and long-term scales (Matero 2000:80). Çatalhöyük is unique in that much of the site is in a dynamic rather than a static state. Until recently, the in-situ archaeology was in the process of excavation and interpretation as much as the exposed structures. There were two excavation areas on-site under permanent shelters, the North Area and the South Area, in which several Buildings and Spaces have been exposed and placed on display for extended periods, roughly 24 buildings in the South and 20 buildings in the North. On display are floors, walls, ovens, burial pits, installations, and painted walls. These shelters have been constructed to allow the long-term display of Neolithic buildings.

In the South Area, excavations have focused on the temporal sequence of the site, looking at continuity and change through roughly 800 years of occupation of the site (Figure 5.3). The depth of the archaeology, with houses from different phases on display, demonstrates the build-up of the site and emphasizes the Neolithic timeframe. Some walls remain from the Mellaart excavations in the 1960s in addition to the Çatalhöyük Research Project excavations. The long sequence of bricks and mortar in the South Area on display represents the walls of successive houses built on top of one another and changes in building resources and practices (Love 2013).

The North Area is a neighbourhood presented as a snapshot of predominantly the middle and late phases of the site (Figure 5.4). The buildings on display were excavated from 1997 to 2017. While there are many architectural similarities between the North and South Areas, the North Area buildings are somewhat unique in that a great conflagration burned several buildings, altering their chemistry and subsequent preservation.

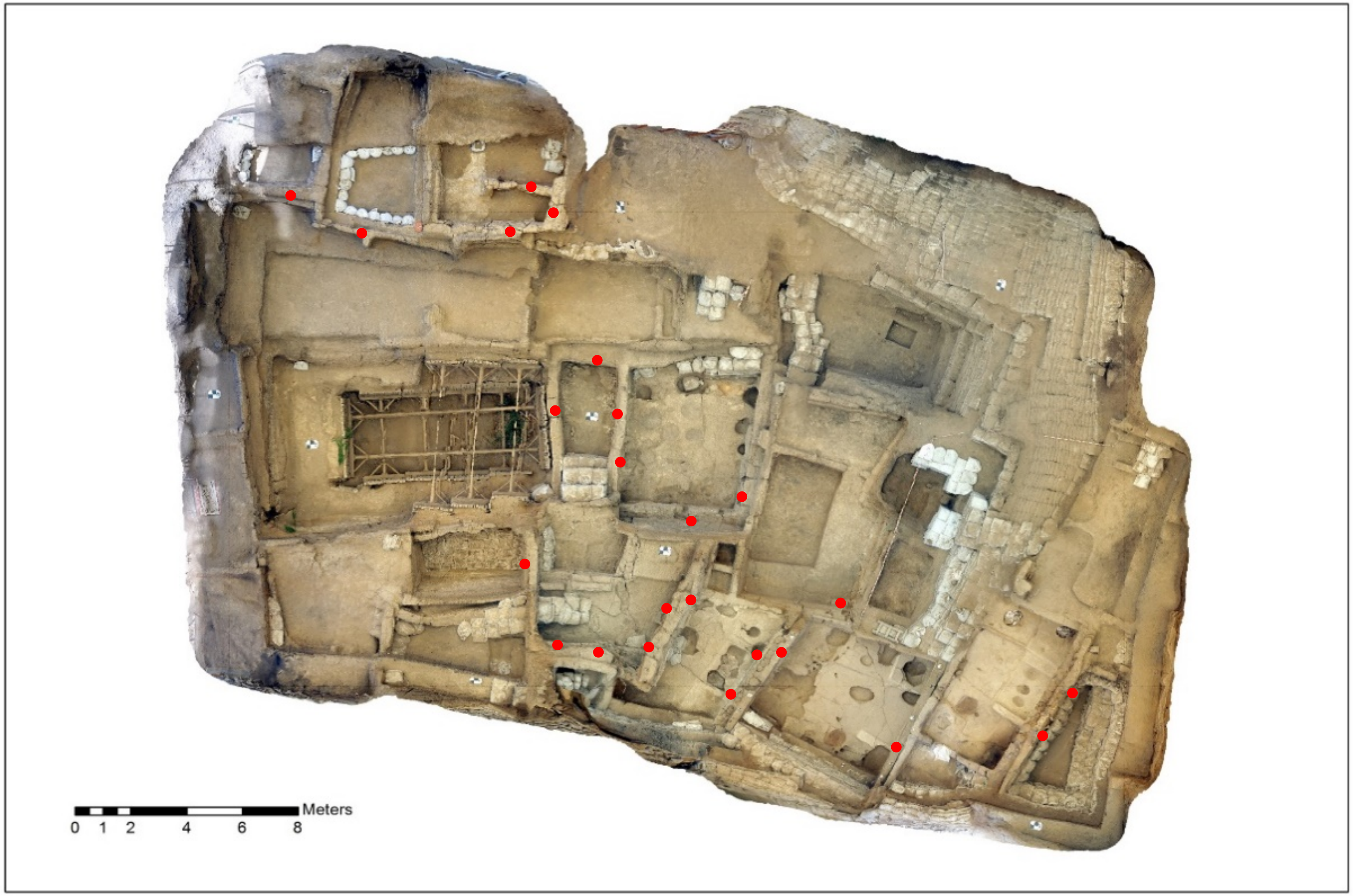


Figure 5.3 South Area. Orthophoto generated from UAV *based structure from motion (Lercari 2015). Sampling locations for the samples used in this PhD study are highlighted in red.*

Figure 5.4 North Area. Orthophoto generated from UAV based structure from motion (Lercari 2015). Sampling locations for the samples used in this PhD study are highlighted in red.

5.4 Deterioration

The following is an expansion of the discussion of earthen architecture deterioration from Chapter 2 with a focus on the agents of decay at Çatalhöyük. Earthen architecture has a non-linear pattern of deterioration, and the environment affects the type, severity, and extent of its attrition. Destabilizing factors such as rainfall, humidity and moisture, and annual and diurnal temperature variation all contribute to deterioration (Cooke 2010). Some types of deterioration can cause catastrophic or rapid loss, while others occur more gradually, but it is essential to understand the correlation between events (ibid). The corners of earthen buildings are generally the weakest points of construction and are most susceptible to erosion and deterioration.

Çatalhöyük has problems with all the agents of deterioration listed below to varying degrees. The shelters, particularly the North, seem to exacerbate some issues such as fluctuations of relative humidity and temperature, water damage, and salt efflorescence. Other issues, such as animal damage, have traditionally been a problem throughout the site but have improved over time. The information presented in sections 5.4.1 to 5.4.3 are site specific accounts of the types of deterioration detailed in Chapter 2.

5.4.1 Shifting environments

One of the problems that structures at Çatalhöyük face is the rapid desiccation of the plasters and mudbricks as the walls are excavated. Rapid desiccation is a problem inherent in the mudbrick (Cooke 2008). Also, plasters are sometimes removed as part of the excavation process, making the mudbrick underneath even more susceptible to deterioration. Remaining plasters on the exposed surfaces of the mudbrick walls tend to crack and sheer throughout. As discussed in Chapter 3, interventions such as block-lifting, backfilling, and sheltering have all been employed at the site to achieve long-term preservation of the decorative plasters and in-situ structures (Rico 2004). The conservation team at Çatalhöyük has invested much time and energy in consolidating the plasters in-situ. Observations suggested this practice keeps the plasters in place for a few seasons longer (Pye 2006), but it has not proven viable for long-term preservation.

Once excavation begins and the depositional environment is disturbed along with the thermo-hygrometric equilibrium, this triggers the cycles of deterioration for the in-situ structures. Destabilization can occur on both the macro- and micro- scale, exacerbating pre-existing conditions and creating new structural instability. The rate at which the buildings are excavated can have a significant impact on how quickly it deteriorates once excavations have finished (Matero and Moss 2004). The results of a study carried out by Matero and Moss (2004) demonstrated that quick excavation leads to rapid environmental change and, consequently, swift desiccation. Slower excavation allows for some level equilibrium to be reached with the surrounding environment, decelerating attrition (Ibid). Changes in thermal coefficients, including diurnal and annual shifts, due to the presence of water and water vapour cause excavated earthen surfaces to become climatically active. Through the presence of water (liquid) and moisture (water vapour), both processes causing additional disruptive internal pressures within the pores and microcracks of the material, resulting in disaggregation, flaking, and detachment (Matero 2015). Additionally, earthen materials, predominantly clays, deform plastically over time (Velde 2008). Salts present in mudbrick can either crystallize or hydrate depending on the environmental parameters created, leading to disruptive internal pressure within its pores.

Wind can impact earthen architecture negatively in two ways: (1) by carrying particulates across the surface, causing abrasion; and (2) by hastening evaporation (Rico 2004; Cooke 2010). These two conditions lead to surface exfoliation and cracking, but they can also alter the dynamic load of a wall causing it to become structurally weak (Hughes 1983). The rapid environmental change that occurs with wind events can also create a moisture differential decreasing the relative humidity locally at the surface of the wall; additionally, the change between the external and internal surfaces of the wall leads to shearing (Péron et al. 2006). For the soluble salts, this event presents a further opportunity for efflorescence and sub-florescence to occur. Wind damage can also cause the plaster to shear away from the wall, taking sections of mudbrick with it. Wind damage is particularly prominent under the North Area Shelter at the site.

5.4.2 Moisture

Water, in its various forms (e.g. rain, ground, vapour), poses the biggest threat to earthen buildings and can be thought of as the 'activator' of erosion (Cooke 2008). Water can cause materials, specifically clays, in mudbrick to expand or contract, or even become liquid if enough is present (Crosby 1983). Once the water has compromised the earthen architecture, it can cause the material to lose both tensile and compressive strength (Crosby 1983). Capillary action is a problem in most earthen architecture and Çatalhöyük is an excellent example of the problems caused by capillary water damage. Capillary action refers to the absorption of groundwater, rising and spreading through the material, leading to clay shrinking once evaporation at the surface has occurred (Crosby 1983). Groundwater often carries salts, which is an additional hazard, as discussed in Chapter 2.

The most pronounced threat to the exposed buildings is that of basal erosion whereby a higher concentration of moisture in the lower part of a wall, due to capillary rise leads to undercutting (Figure 2.8). This main problem arising from this deterioration at the base of the wall is the loss of under-loading support, which introduces loadbearing eccentricities into the structure and may eventually lead to overturning (Goudie 1986; Illampas et al. 2013). Fluctuations in the environment within the shelters cause cycles of condensation and evaporation, leading to humidification and desiccation of the earthen archaeological substrate. Furthermore, hydration and shrink-swelling phenomena of clay with additional contaminates can have a catastrophic impact on earthen architecture.

Capillary rise transports both moisture and soluble salts into the pores of the structures. Relative humidity fluctuations create mechanical stress with the soluble salts identified within the earthen architecture. Soluble salts cause deterioration by way of transitioning, moving through the pores when deliquescent, then efflorescence and sub-florescence leading to disaggregation. The salts currently identified at Çatalhöyük are: sodium chloride/halite (NaCl), potassium chloride/sylvite (KCl), sodium nitrate/nitratine (NaNO3), potassium nitrate/niter (KNO3), potassium magnesium chloride/carnallite (KMgCl3·6(H2O)), calcium sulfate dihydrate/gypsum (CaSO4-2H2O), calcium sulfate hemihydrate/bassanite (2CaSO4-H2O) and sodium sulfate/thenardite (Na2SO4) (King 2014) (Table 5.1).

Table 5.1 Salts identified at Çatalhöyük with relevant properties

Salt	Crystal structure	Mineral Type	Solubility (20°C)	Molar Volume	Deliquescence Relative Humidity (%)				
					10°C	**20°C**	**30°C**	**40°C**	**50°C**
Bassanite (2CaSO4-H2O) Third most common on site	Monoclinic	Sulfate	3.0g/l	55.04 cm^3/mol	See Gypsum				
Carnallite (KMgCl3•6(H2O))	Orthorhombic	Chloride	-	173.7 cm^3/mol		59			
Gypsum (CaSO4-2H2O)	Monoclinic	Sulfate	2.4g/l	74.69 cm^3/mol		99			
Halite (NaCl) Most common salt on site	Cubic	Chloride	6.135 mol/kg	27.02 cm^3/mol	76.60	77.60	75.20	74.70	74.10
Niter (KNO3)	Orthorhombic	Nitrates	3.108 mol/kg	48.04 cm^3/mol	97.00	92.30	90.50	87.90	85.00
Nitratine (NaNO3)Sodium Nitrate/ Cubic Niter. Second Most common	Trigonal	Nitrates	10.347 mol/kg	37.60 cm^3/mol	78.00	77.10	72.40	70.10	67.30
Sylvite (KCl)	Cubic	Chloride	4.595 mol/kg	37.52 cm^3/mol	88.30	85.70	84.00	81.20	80.00
Thenardite (Na_2SO_4)	Orthorhombic	Sulfate	162g/l	53.11 cm^3/mol	85.60	86.60	87.30	87.90	88.40

5.4.3 Biological damage

Biological activity is an unavoidable element of the decay of in situ earthen architecture. Vegetation is problematic at earthen sites but, in some instances, aids in holding a wall in place. Plant roots can be invasive, causing structural damage; however, once the roots are in place, they can help hold an earthen wall together. The level of damage is dependent on the diameter of the root structure and the lifespan of the plant itself; otherwise, the result will be the physical loss of the wall (Chiari 1985). Vegetation can trap moisture and create microclimates, causing differential fluctuations of relative humidity and temperature (ibid). Plants can be used to absorb water along the base of a wall or can be strategically placed at a site to control wind abrasion (Horne 1994). Invasive vegetation is a constant issue at the site, particularly around the interior perimeters of the shelter buildings.

Animals such as birds, insects, reptiles, and mammals large and small can cause significant amounts of damage to an earthen site. Burrowing is a concern, as it removes the soil, which can lead to a collapse in addition to the loss of information about the structure (Rainer 2008). At Çatalhöyük, an infestation of ground squirrels has left meandering tunnels, and dens thought out the walls and features of the site. Other animal issues include relocating materials for nests, altering the soil composition through eating and waste cycles, and abrasion.

Humans can also cause a tremendous amount of damage to a site through intentional and unintentional actions (Rainer 2008). Human activity also includes deliberate defacing of architecture, slow erosion from foot traffic, damage from careless behaviour at a site, inappropriate conservation, and archaeological excavation. Unfortunately, at Çatalhöyük visitors make their way to the shelters unchaperoned and stray from the walkways, climbing into buildings and across sandbags. This behaviour is dangerous for visitor safety as well as the preservation of the in-situ structures.

5.5 Methodological History of Conservation at Çatalhöyük

5.5.1 History

At Çatalhöyük, conservation management planning has had to remain both flexible and consistent. It is a constant negotiation to balance research goals, heritage management, and questions of authenticity in a shifting political climate. Moreover, as scientific research moves exponentially faster, maintaining best-practice standards in viable conservation plans can be challenging. All these factors impact treatment rationales and short- and long-term conservation planning. The current excavations at Çatalhöyük have been ongoing for over two decades, with the overarching aim of the project focused on reflexive archaeological practice, and this has also held for conservation. In the archaeological research, the reflexive approach has remained mostly unchanged, though many research questions, interpretations, practices, and technologies have shifted how the site is understood. This reflexivity is just as true for the conservation practice at the site. Though aspects of the program have allowed for more advancement than others, much has been learned from both the failures as successes.

Approaches to conservation management and objectives have varied with changes in conservation staff, overall project aims and proactive responses to previous conservation treatments. As such, how the architecture is treated has gone through several methodological incarnations. For much of the project history, the conservation program centred around consolidation of the earthen buildings for stabilization and display (Matero 2000; Pye 2006). The construction of permanent shelters over the South (2003) and North (2008) excavation areas has had a significant impact on the preservation of the in-situ archaeology. Though a significant step in long-term preservation, shelter design has resulted in a trickle-down effect of how the archaeological material is treated. Shelter construction has caused an overall shift in the conservation approach, moving from treatments solely based on the archaeological substrate to treatments based on the climate surrounding the in-situ archaeology.

5.5.2 Teams

Preservation work at Çatalhöyük began in the 1990s when a team from University of Pennsylvania established on-site conservation and laboratory testing at the site and developed best practice suggestions for the preservation of the newly excavated buildings, chiefly testing in Building 5 (Matero and Moss 2004). A system of aqueous polymer application to the wall was established as an interim stabilization method, while the long-term management plan was still under development. In 2003, the conservation team underwent a transition, with a group from University College London headed by Elizabeth Pye taking charge. During this transition, some changes were made to the polymer application across the site; however, the overall concept persisted due to its perceived success in stabilisation.

It was not until 2012 that the polymer system was called into question, and other methods of preserving the earthen architecture were sought. There were two driving forces in this re-evaluation: 1. after two seasons of It working with the consolidation treatment, this author found the number of times walls needed retreatment just in a single season, to be an ineffective use of resources; 2. The site received a UNESCO World Heritage Designation; the ICOMOS review panel also decided that a more effective treatment should be sought. It should be noted that the North shelter was constructed after the completion of Matero and Moss' study and had only been in place for a short time before Pye left the project. As the subsequent environmental monitoring provided below demonstrates, the structure significantly altered the conditions initially assessed, precisely temperature and humidity (Lingle 2014), which has consequent implications for the success of the treatment.

5.5.3 Permanent Shelter Construction

At Çatalhöyük, two separate efforts were made to create shelters over the South (2003) and North (2008) Areas of excavation. While the shelters allow the archaeology to be viewed year-round and protect it from catastrophic loss due to rain, snow and damage during backfilling and uncovering processes, other slower agents of deterioration have become evident. The shelters were designed to include foundations that would have minimal impact on the archaeology, provide adequate load bearing on a site of variable compaction, protect from extreme weather conditions with high wind uplift and heavy snow loads, and promote adequate airflow during the hot summer months of excavation (Farid 2013), however in practice the design and the performance could not be more opposed. While the shelters can be considered successful interventions in relegating immediate catastrophic damage, monitoring at the site has shed light on the ways in which they contribute to deterioration, as discussed below.

5.5.4 History of the South Shelter

In 2003, a shelter was completed over The South Area of the site, created by Turkish architect Atölye Mimarlik. The design is a concrete plinth and a steel-frame truss system superstructure, covered by a corrugated polycarbonate material that includes removable panels (Farid 2013). Drainage channels were placed immediately outside the foundation walls to carry rainwater off-site. These channels extend to, and cut through, the 1960s spoil-heap to the west (ibid). Over the past 16 years, the shelter has faced some issues with water runoff into the shelter and drainage blockages. The polycarbonate walls and roof are severely suffering from UV degradation and overdue to be replaced, but a more long-term solution was never funded. During the 2018 excavation season the detachable sidewalls were not replaced at the end of the season, as a result, during the winter snow-filled the shelter, eventually exacerbating the cracking that occurs across the archaeological structures (Figure 5.5).

Figure 5.5 South Area with snow build-up in December 2018. Photograph was crowd sourced through Facebook.

5.5.5 History of the North Shelter

Even with the outstanding issues with the South Shelter, it has been the North Shelter with its distinctive shape that has required the most lateral thinking in conservation approaches. The microclimate of the North Shelter has created several conservation challenges and has been a strong driving force in how conservation research has been carried out at the site for nearly the last decade. Though the shelter was designed with some conservation input (Çamurcuoğlu 2007), the performance has not matched the intended effects, and the result has in some ways been disadvantageous to the long-term preservation of the buildings of Çatalhöyük.

> '…To minimize this strain on the archaeology as well as on the excavation team, a metre-wide, continuous concrete plinth requiring minimal excavation was built to support the entire structure and shallowly constructed on the surface of the mound…. The shelter was designed to have a softer form to blend in with the natural topography and be aesthetically pleasing to the eye... The roof structure, which will be constructed of laminated timbers, will follow the gradient of the hill down to the surface and arise from a central point. In this form, the higher parts of the shelter will provide good air ventilation (with folding side panels) whilst the lower sections will create a slope for an effective drainage system (a channel made of pre-cast cement) as well as making the structure more durable against heavy wind in winter. For the final stage a protective cover, constructed from polycarbonate panels, will be installed. Polycarbonate can distribute daylight equally inside the shelter, which is vital for the recording of archaeological sites and also for viewing them...' *(Çamurcuoğlu 2007)*

In practice, however, improved environmental monitoring has shed light on problems within the archaeological walls. Studies of the shelter performance were carried out in 2014 and again in 2016, the results of these studies yielded some surprising results (Lingle 2014; Lingle Forthcoming). A Greenhouse effect occurs under the North Shelter in summer months due to the lack of ventilation. Heat, ultra-violet rays, and reduction of airflow create issues for people under the shelters as well as for the in-situ structures. In winter months, freeze-thaw cycles cause additional mechanical stress on the in-situ archaeology. Snow build-up on the western face of the shelter and poor thermal buffering causes condensation within the shelter, which drips onto the archaeological surfaces. In the summer, temperatures can reach 50°C; to make working conditions bearable the adjustable flaps of the shelter must be opened to allow greater airflow. The airflow can lead to abrasion of the surfaces, bringing with it particulates and contaminants from the outside to exacerbating the problem. Even when the flaps are shut, the gaps in covers of the shelter allows particulates to enter and fails to channel water runoff adequately. To make matters worse, the shallow foundations of the superstructure are on the incline of the mound, causing the shelter to slide to the north (down the slope) by approximately 1.5cm every year (Marek Baranski personal communication July 2016).

5.5.6 Environmental Monitoring

One substantial challenge at the site was to create a comprehensive system for monitoring the in-situ archaeology. Large-scale heritage sites are inherently difficult to monitor and objectively interpret. At Çatalhöyük, the volume of exposed archaeology was challenging to monitor but also the varying excavation strategies of the North and South Areas created their own documentation challenges. The climate under the North Area has been elucidated with implications for the South Area as well. There are seventeen TinyTag® environmental data loggers placed around the site, including one external data logger. These allow the conservation team to understand the full picture of what is happening climatically around the in-situ archaeology. Before the monitoring was in place, the environment could only be guessed at and was not fully considered when designing treatment strategies. It is interesting to note that earlier treatment strategies (i.e. polymerization) were considered effective (Matero 2000; Pye 2006; Pye and Cleere 2008) before the construction of the shelters. Environmental studies focused on the summer months with minimal data for the rest of the year (Rico 2004; Çamurcuoğlu et al. 2015).

Before 2013, (due to the complexity of the site and difficulties with limited conservation team continuity) condition monitoring methods were based on ad-hoc subjective assessments. As a result, the limited data collected was qualitative, and treatments could only be employed as a response to an identified problem. Storing the information in an accessible format was also difficult as the conservation database was designed for use on conserved objects. In response, thanks to a grant from the Archaeological Institute of America (AIA) and a collaboration with University California Merced, the Çatalhöyük Digital Preservation Project (CDPP) was created to utilize digital technologies in conjunction with current monitoring strategies to build a comprehensive view of the site in its current state, as well as to create informed insight into the future (Lingle and Lercari 2017).

To create an informed methodology for monitoring and conserving the site, the CDPP combined the vast amount of digital survey data collected on-site in the period 2012-2017. The CDPP developed an approach to Çatalhöyük conservation by integrating digital documentation with existing site data, allowing for the utilization of both quantitative and qualitative information. Tools and methods for this project include blending site monitoring data and digital documentation data from environmental data loggers, terrestrial laser scanning, micro unmanned aerial vehicles (micro UAVs), 3D Geographic Information Systems (GIS), and virtual simulation. Creating the foundations of this methodology was time-consuming, and as such, the CDPP focused on the North Area, using 2D and 3D multi-temporal monitoring to document the progressive decay and erosion of buildings and to identify areas of immediate risk. The study, was amended by a year-round environmental monitoring program in 2014, has helped conservators to understand what is happening at the site year-round, not just during the excavation periods (Figure 5.6).

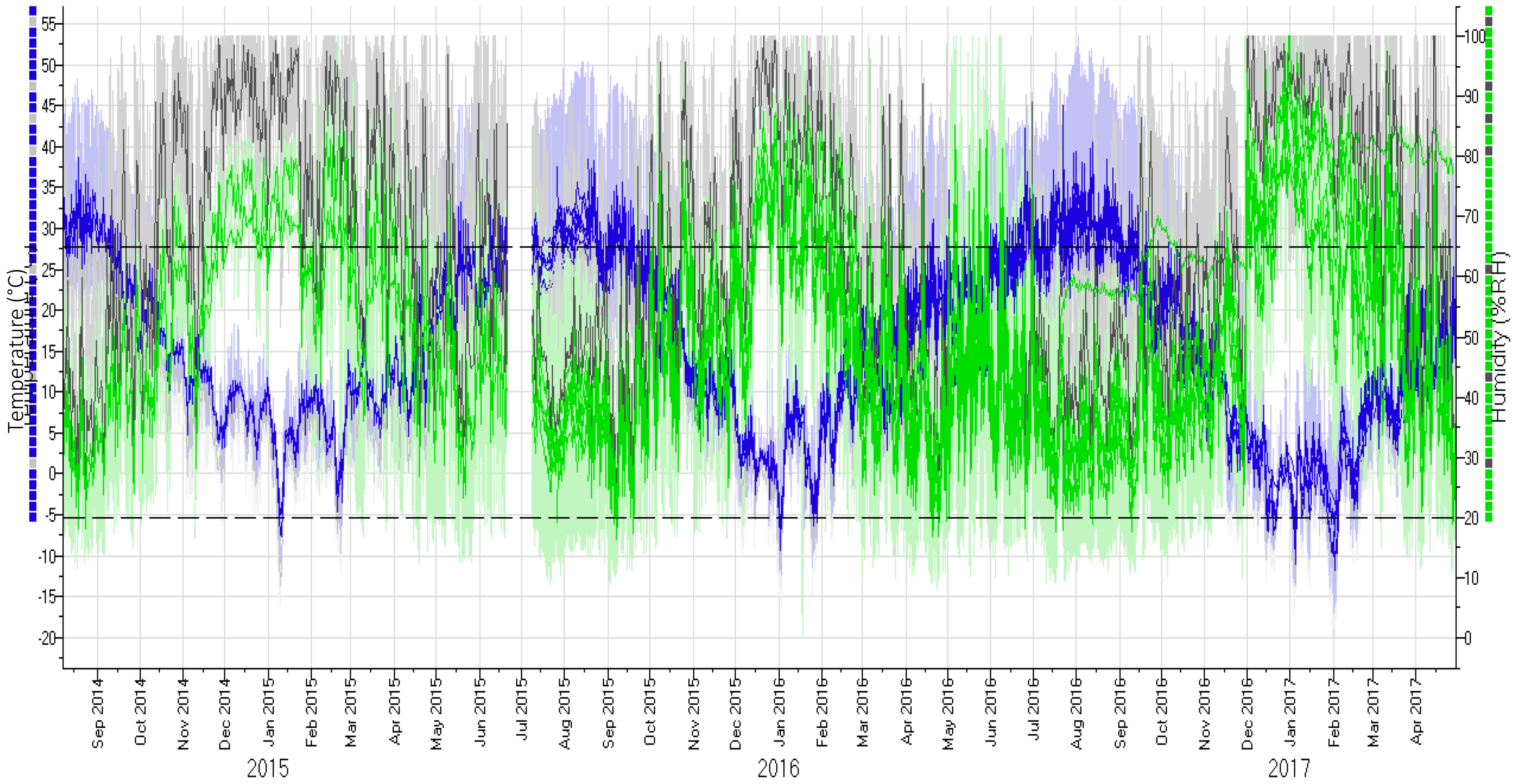


Figure 5.6 Environmental data collected from 2014-2017. Internal shelter temperature(blue), external temperature(lavender), internal humidity(green), and external humidity(black). The horizontal dotted lines mark 20% and 65% relative humidity.

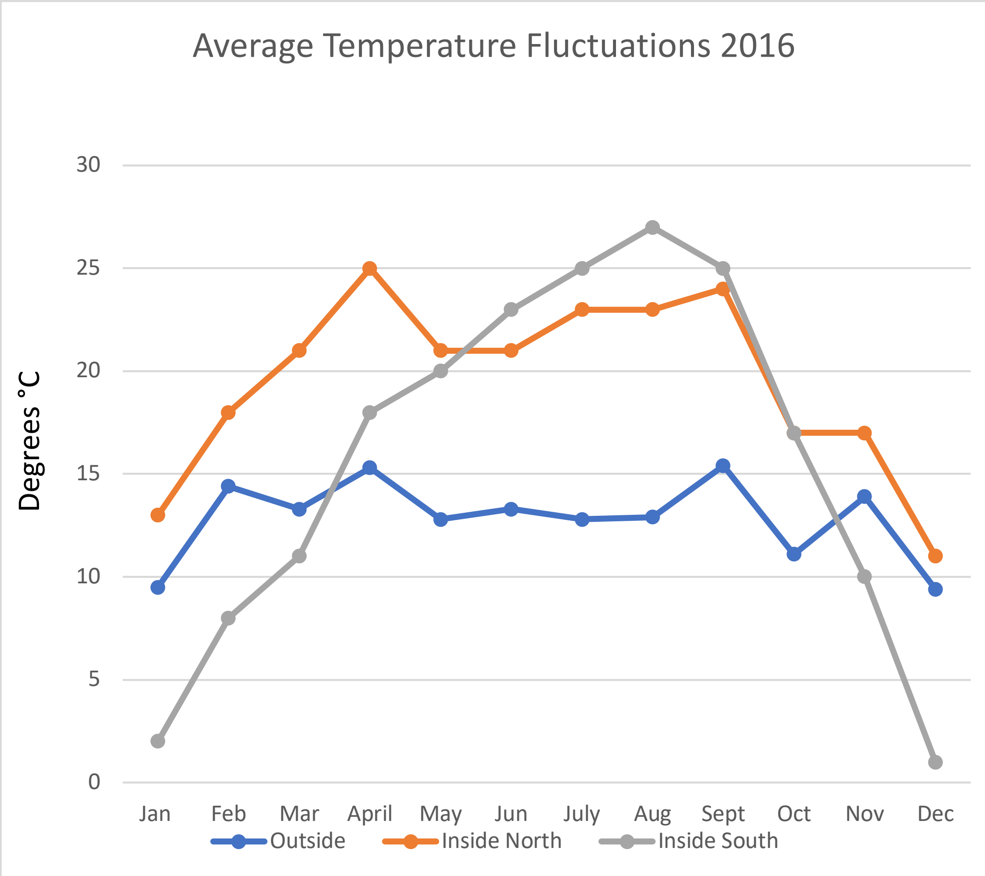


Figure 5.7 Comparison between the Temperature-Range Average of thermal fluctuation inside the South shelter (grey) North shelter (orange) and outside the shelter (blue) (Figure by A. Campiani).

The wide temperature and humidity variations recorded have a substantial impact on the choice of materials for conservation treatments (e.g. the temperature has a significant influence on how polymers dry on the application and performance in the long-term). The evidence indicates that the decay of Neolithic architecture at Çatalhöyük is primarily due to fluctuations in the climate under the permanent shelters (Figure 5.7). Frequent and varied thermal exchanges create environmental stability problems for the in-situ structures (as expanded in Figure 5.8). Using TinyTag® data from 2016, the average daily thermal exchange was calculated to examine the climate under the shelters. The annual average temperature range calculated by the loggers is 19° C, the lowest monthly temperature recorded on January 3rd, 2016 is -14° C and the highest monthly temperature recorded on July 31st, 2016 is 52° C. Under the shelters, the daily temperature difference between the maximum and minimum temperature ranges from 15° C (Winter) and 35° C (Spring).

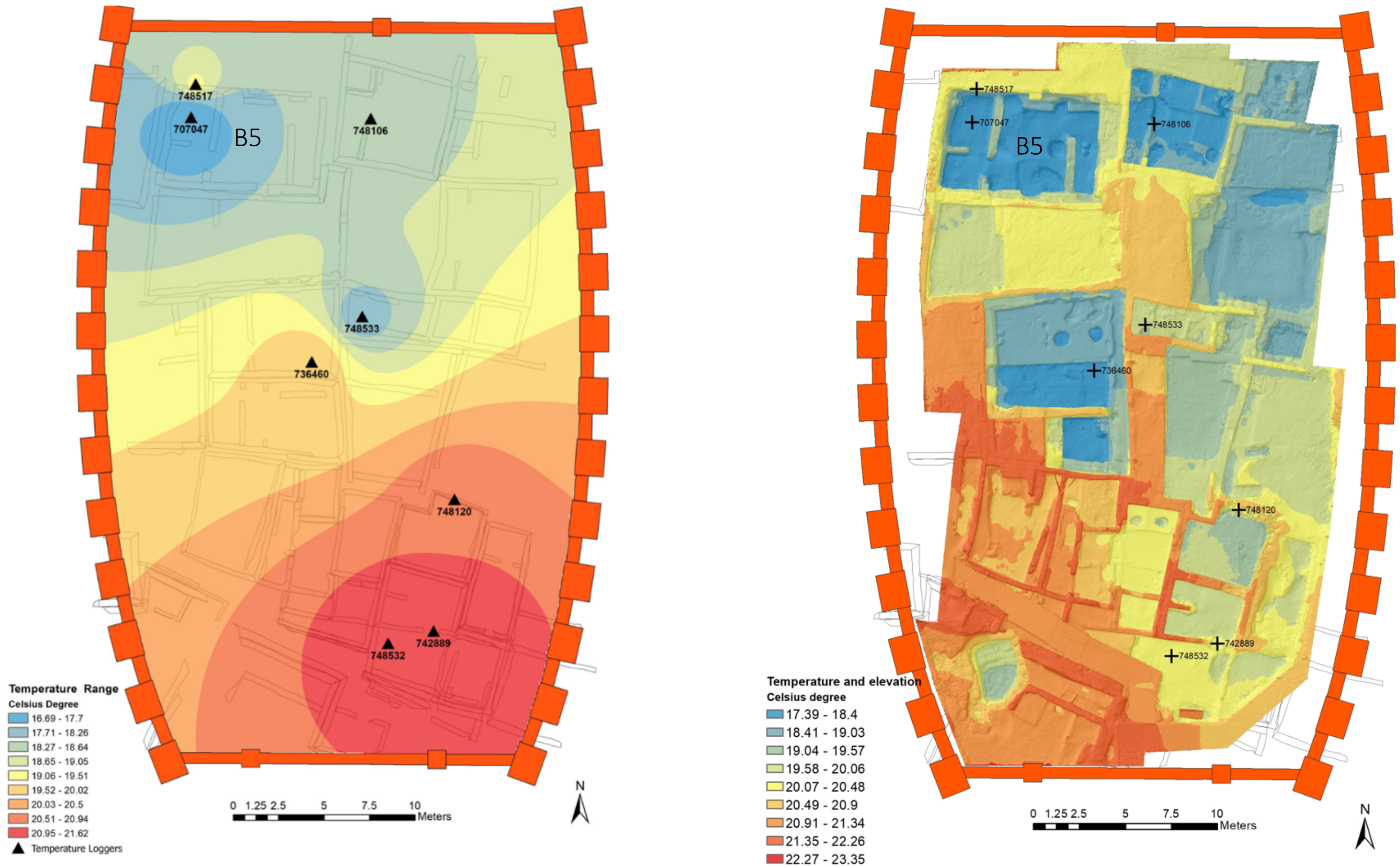


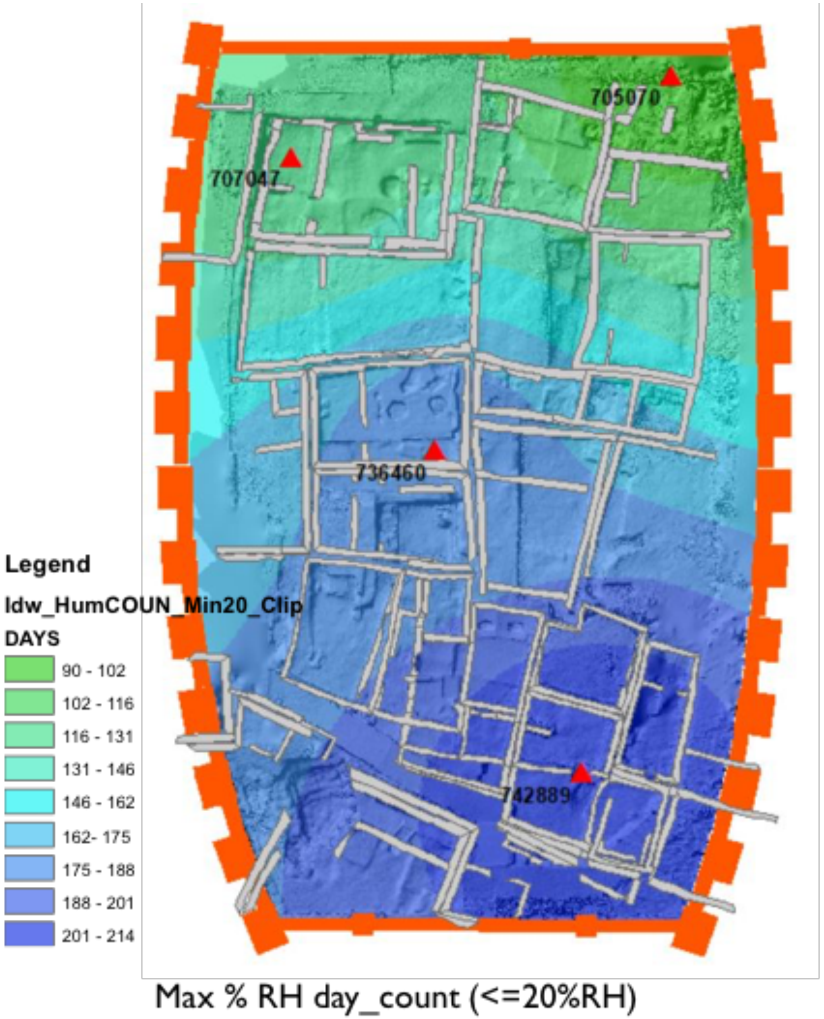
Figure 5.8 Average Range Temperature calculated for the North Area. *Left without adjustment for trench depth and right with adjustment for trench dept. To obtain these spatial-temporary climate maps of temperature and humidity distribution under the shelter an Inverse Distance Weighted (IDW) interpolation technique was used. This method is a deterministic interpolation method that estimates the value at unknown points using the sampled values and distance of surrounding nearby known points, without any statistical assumption abstracted from the dataset (Figure by A. Campiani).*

Upon closer inspection, the environment under the shelters presents an even more complex picture. The CDPP study of the temperature data showed a wide variety of environments across the shelter. The average temperature fluctuation registered in the southern stations of the North shelter shows higher records compared with the northern stations. The climate map suggests an area of higher thermal excursions in the South-East corner of the shelter. Medium value variation is more likely to happen in the centre and decrease toward the North, where lower fluctuations were registered in the North-West corner. A difference of more than 2 °C is registered between the logger on the floor inside B5 and the one on top of the north wall (Figure 5.8). This is due to deeper buildings present lower thermal excursion, while the architectures closer to the surface are more subject to temperature fluctuation. B5 was excavated in 1998, and its floor level remains 3.5–4.5 meters below the ground level (Campiani et al. 2019).

On a given summer day, the relative humidity within the shelter can fluctuate from 5% up to 70%. In the winter months, relative humidity ranges from 40% to 100%, presenting the highest risk for salts to deliquesce, move, and re-crystallise multiple times in a day. Soluble salts included in the mudbrick at Çatalhöyük deliquesce at roughly 65% RH (Table 5.1); below this percentage, the salts re-crystallise and fluoresce. Thus, any time that the internal shelter RH goes above and then below the deliquescence point, one can expect material loss and erosion to occur. Alternatively, when the humidity drops below 20% RH, the mudbrick begins to desiccate, triggering delamination and material loss occur (Ravi et al. 2004). To study the phenomena occurring under the shelters, these two points of environmental risk were selected for mapping and study as part of the CDPP monitoring project (Campiani et al. 2019) (Figure 5.9). While the TinyTag data identifies the frequency which these parameters are met on a daily and annual scales, the CDPP project focused on average trends for a more holistic view of what is happening to the site.

When dealing with conservation issues in earthen architecture, it is essential to consider both temperature and relative humidity and their inverse relationship; for example, even dry air can have a high degree of relative humidity in low temperatures (Ridout 2008). This relationship was the driver for combining the temperature and relative humidity data to create an environmental heritage risk value that estimates the threat to the site (Figure 5.10).

For temperature, how many days a month there is a fluctuation bigger than the average value plus its standard deviation was computed. As the three datasets (days with extreme temperature fluctuation, days with high RH, days with low RH) are different scales, the data was normalised to be able to examine what areas have more extreme values of different criteria. These normalised Z-scores can be averaged at each position, wherein an 'average point' that saw average numbers of extremely fluctuating temperatures, days with high RH, and days of low RH would have a value of 0, and positive values mean that a point experienced these damaging environmental traits at higher than average rates (Campiani et al. 2019). This result is an absolute, cantered, and normalised risk value is given the three parameters, % RH above 65, % RH below 20, and days with a temperature fluctuation > average +1 standard deviation, where all parameters are equally weighted. This map now serves as the foundation for further investigation of conservation issues in the North Area at Çatalhöyük (Figure 5.12). The CDPP hopes to gain additional funding to apply this level of study and analysis to the South Area of the site and its microclimate.



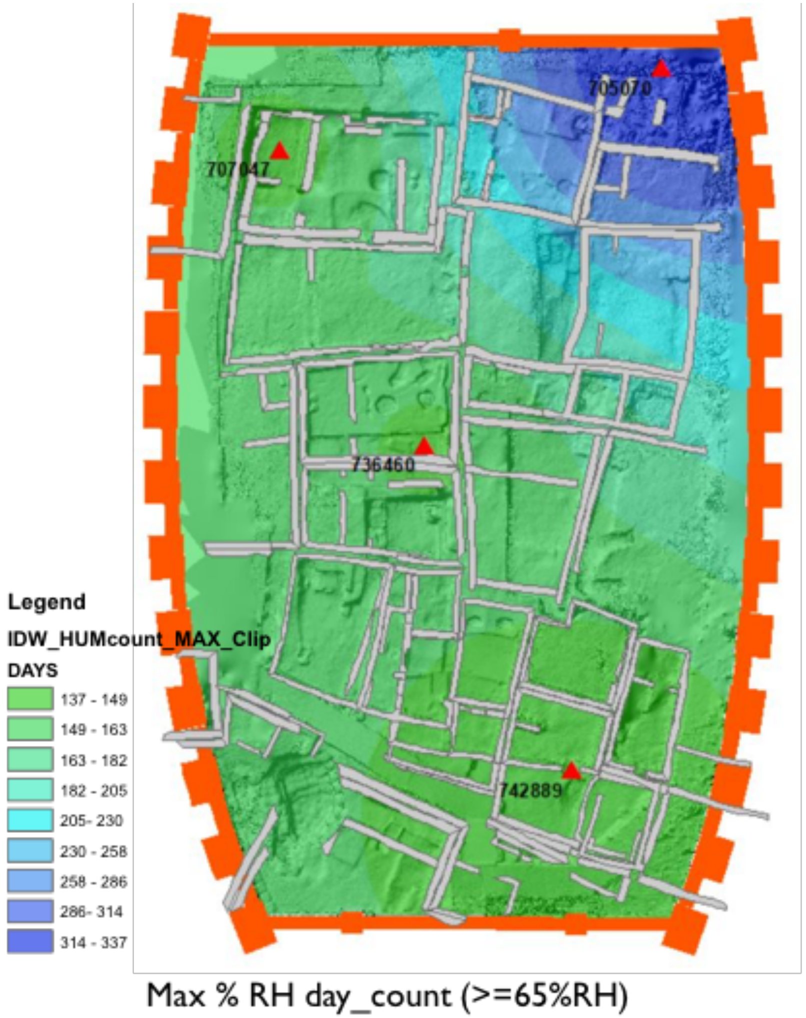


Figure 5.9 North Area Relative Humidity Ranges. Humidity models of relative humidity fluctuations. Left day count where RH dropped below 20%. Right day count where RH rose above 65% (Figure by A. Campiani).

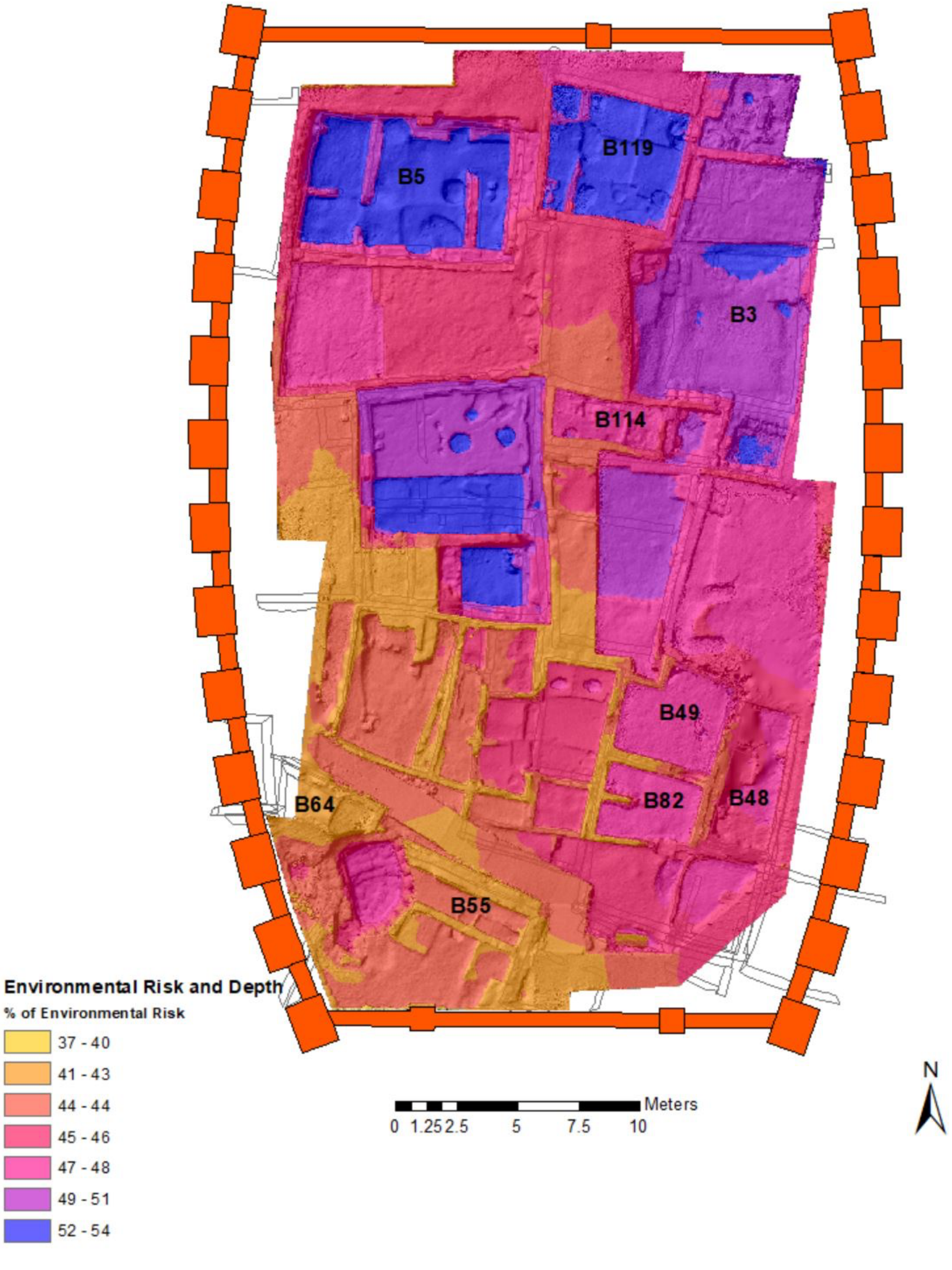


Figure 5.10 Interpolation of data from Figures 5.8 and 5.9 Creating a snapshot of risk and the potential for deterioration under the North Area Shelter (Figure by A. Campiani).

5.5.7 Quantifying Deterioration

In order to manage, analyse and visualise the quantitative and qualitative data collected at Çatalhöyük, spatial analytical tools available in the ESRI ArcGIS platform were utilised by the CDPP team. This platform allowed the combination of 3D models of buildings surveyed yearly by TLS with qualitative conservation assessment data and environmental data (temperature and humidity) as well as with surface material loss data obtained by computing the difference of TLS point clouds of North Area features recorded at different times (Campiani et al. 2019). Figure 5.11 shows one example of the feature level analysis utilising TLS point clouds and CloudCompare software. The top image is the TLS point cloud collected in 2014, beneath that the point cloud from 2016 is overlaid in red, blue areas denoted significant areas of change. Using this information, the material loss for this period can be quantitatively measured and calculates cumulatively to 0.00594627m^3 or 5.95 litres of erosion.

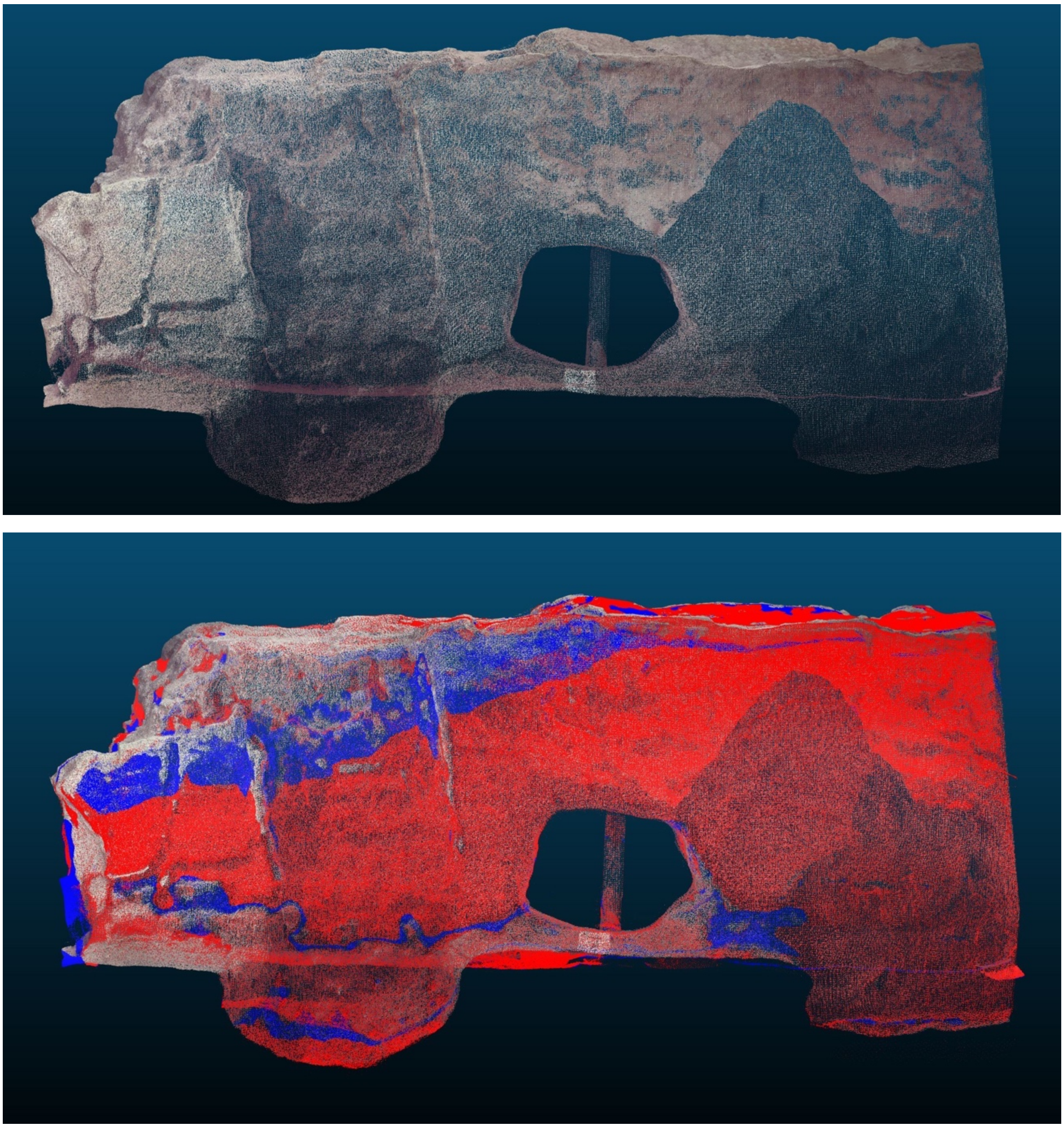


Figure 5.11 Building 5, Point Cloud of Feature 229 in 2014 and with the overlaid of Significant Change areas (blue) when aligned with 2016 Point Cloud (red) in CloudCompare (Figure by A. Campiani)

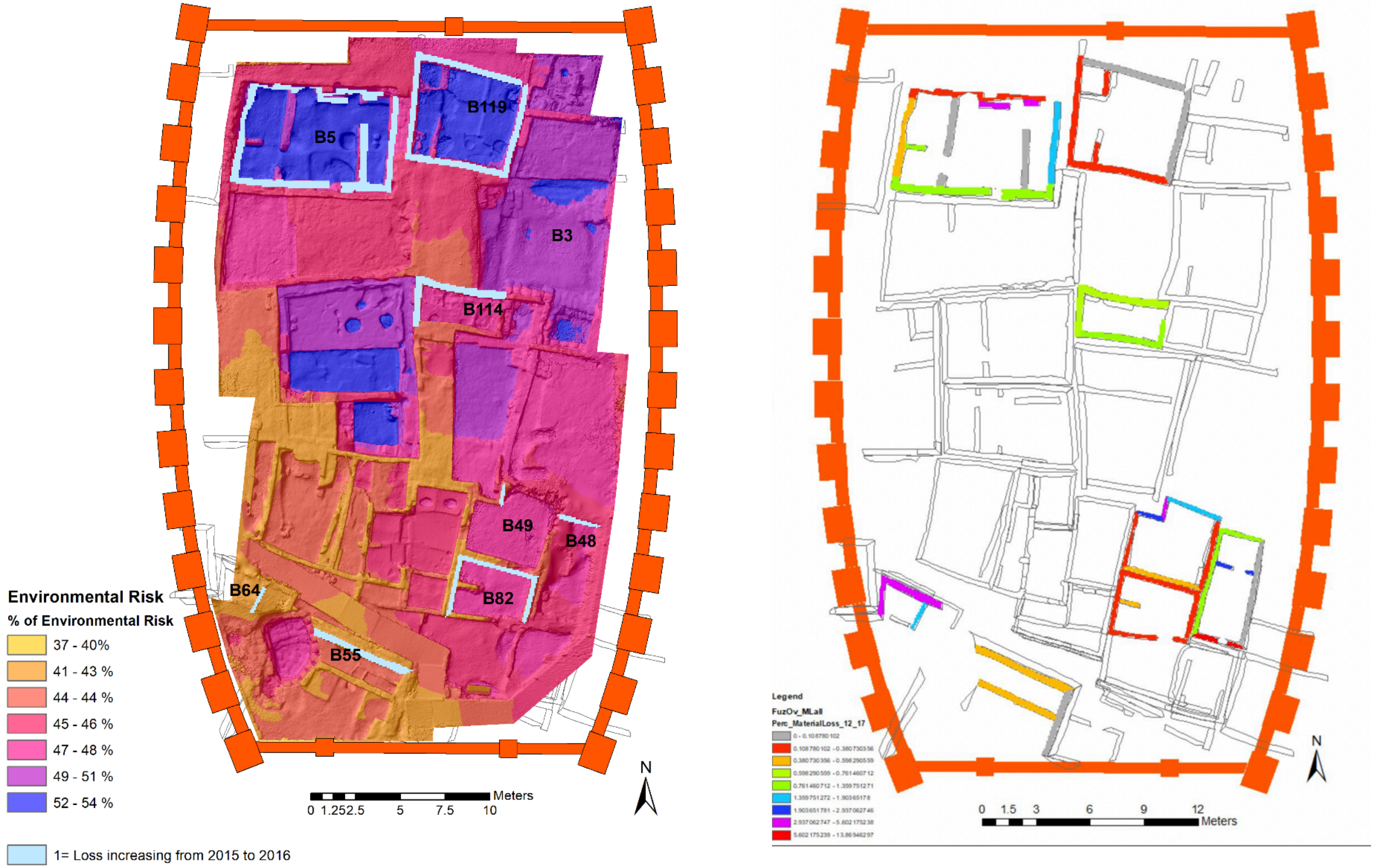


Figure 5.12 Environmental risk and deterioration maps. Left. Environmental Risk interpolation map with areas of loss which increased in over-all volume from 2015-2016. Right. ArcGis map with volumetric measurements for deterioration *the highlighted features with total loss volume from 2012-2017 (Figure by A. Campiani)*

5.5.8 History of consolidation at Çatalhöyük

Despite the grueling pace of excavation, James Mellaart realized early on that the exposed architectural features quickly developed cracks and became unstable, forcing him to excavate horizontally stacked building levels one by one (Mellaart 1964). Though the focus of any conservation work was on painted walls and plaster features for removal, efforts were made to address rapid deterioration. Besides cracking upon drying, paintings began to fade or to change colour once exposed (Mellaart 1966). For this reason, unearthed paintings were immediately documented through line tracing on cellophane sheets, photographed and treated with polyvinyl acetate (PVAC) emulsions before their removal from their original location (Matero 2000). Once removed, paintings were in typically transferred to the Museum for Anatolian Civilizations in Ankara, where they were further treated with PVA (Myers 1999). No conservation measures were carried out for in-situ preservation of the architecture, as open display of the buildings was not was not an aim of Mellaart's research (Matero 2000).

Following the consolidation carried out in the 1960s with polyvinyl acetate (PVAC), this approach was again brought to the site in the 1990s (Matero 2000). When the University of Pennsylvania team resumed conservation work at the site consolidation efforts were extended to the in-situ walls. Prioritizing in-situ preservation when viable rather than removal to create a conservation program for open display**.** The practice of attempting to strengthen walls by polymerization was re-established at Çatalhöyük utilizing laboratory testing (Matero 2000) and continued to some extent, unchallenged for nearly 20 years. Through laboratory and in-situ tests, several possible consolidants, both organic and inorganic, were evaluated based on several criteria which included, amongst others: depth of penetration and distribution of consolidant; mechanical durability; physical appearance; reversibility; and ease and safety of application (Koppelson 1996). Comparative product testing of three types of consolidants including an epoxy resin, an acrylic resin and ethyl silicate, both the laboratory and in the field were inconclusive (ibid). A further study was carried out to identify an appropriate consolidant (Matero and Moss 2004). Assessment methods in both studies were highly empirical, and the results demonstrated that salt recrystallization sometimes occurred at the surface-substrate interface and that the correlation with deterioration included flaking, delamination, and detachment (Koppelson 1996; Matero and Moss 2004). Finally, an acrylic emulsion diluted in water (PVAC) was selected and used for surface consolidation (Matero 2000). While it performed the best during laboratory tests, the only factor which was modelled was desiccation; other environmental factors were not tested (Figure 5.13). Results were judged on an observational basis without any depth of penetration evaluations.

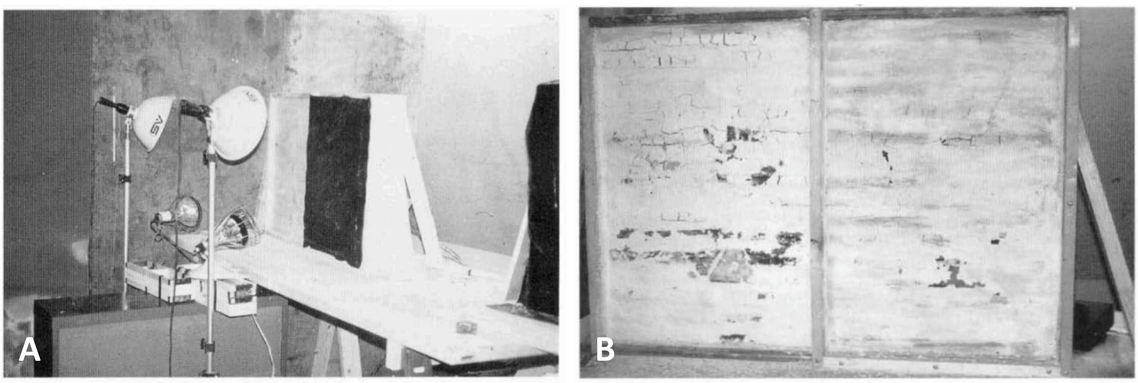


Figure 5.13 Images of laboratory setup from Matero and Moss' consolidation studies. A. Laboratory fabricated panels from materials sources near Çatalhöyük; panels were exposed to heat lamps to look at protective materials from the impact of desiccation. B. Left side of the panel is untreated, right side was consolidated with PVAC. Photographs by E. Moss (Matero 2000).

Primal (Rhoplex) AC-33 and later Primal B60A, was not initially selected for wall consolidation but as an additive for the grouting mixture for stabilising fissures. Primal AC-33 was also used to stabilise fine cracks and as an adhesive to re-lay flaking plaster. In 2003, following a team transition, spraying Primal AC-33 became common practice (Cooke 2010). Pye (2006) also mentions the injection of Primal AC-33, but this application method is not found in the (limited) documentation for the in-situ structures at the site. What can be gleaned from the documentation is that methods of application and concentration were ad-hoc at best and varied across practitioners. This variation in consolidation strategy is a reflection of external factors, rather than conscientious changes to polymer application: 1. there was minimal team continuity from year to year; 2. From 2004 onward most of the conservation work was being carried out by students studying object conservation with limited experience and typically did not have backgrounds in architectural conservation.

While it was not initially intended for long-term stabilisation, it eventually became part of the annual conservation maintenance and was reapplied when signs of deterioration began to reappear. Primal B60A became a 'fix-all' for both the mudbrick walls and plaster at the site.

Many of the earthen buildings, once excavations finished, were sprayed with Primal so they could be left on open display (Cooke 2008). Though the polymer has some uses on-site, it was in some ways an ill-fated choice. For example, the glass transition temperature at which the polymer loses its rigidity is 12°C for Primal AC-33, which is far below the near 50°C temperatures recorded in the summer months. Additional problems occur with treatments carried out in warmer months as a film-formation temperature above 20°C results in the incomplete coalescence of particles and poor film formation. Distortion occurs during drying due to water movement and shrinkage (Horie 2010). At Çatalhöyük, this process has an effect similar to delamination and spalling, which occurs naturally as the archaeological substrate desiccates. This treatment became a cyclical problem as part of the annual conservation maintenance was the reapplication of Primal when signs of deterioration began to reappear.

Visual examination of consolidation can be misleading, as water mixed with the polymer separates and seeps into the substrate, giving the appearance that consolidation is taking place. When the polymer was reviewed on site in 2005, it was reported to be working effectively (Çamurcuoğlu 2005). The short study reviewed consolidant penetration depth on clay marl samples from the site that were consolidated in the laboratory, observed for colour change and measured for depth. Çamurcuoğlu selected several consolidants: 3% Klucel G (cellulose ether) in deionised water; 5%/10%/25% Primal AC-33 (acrylic dispersion) in deionised water; 8% Plextol (acrylic emulsion) in deionised water; 5%/10% PVAC (acrylic emulsion) in acetone; 4% Paraloid B-72 (acrylic resin) in alcohol were brushed across the horizontal surface of the plaster sample then observed for one minute under a binocular microscope and measured with digital calipers (ibid). No volumes are given for the amount of polymer applied, and the samples were not kept for further analysis. The test found that the penetration depth varied, but recorded depths of nearly half a centimetre for Primal AC-33. However, given the limitations of available equipment in the field, there was no way to evaluate if the observed phenomenon was both the solute and the solvent or just the solvent.

To better highlight the observational phenomena that occurred during Çamurcuğlu's study, this author performed a fluorescence test during the initial stages of this PhD research. Using the methodology established by Zucker et al. (2011), a fluorescent tagger (0.015g/ml Rhodamine B) was added to dispersions of 5%/10%/20% Primal B60A (acrylic dispersion). The samples were allowed to dry overnight before they were divided. The mudbrick samples were cut using the snap method discussed in Chapter 7. The samples were then photographed used ultraviolet light (Figure 5.14).

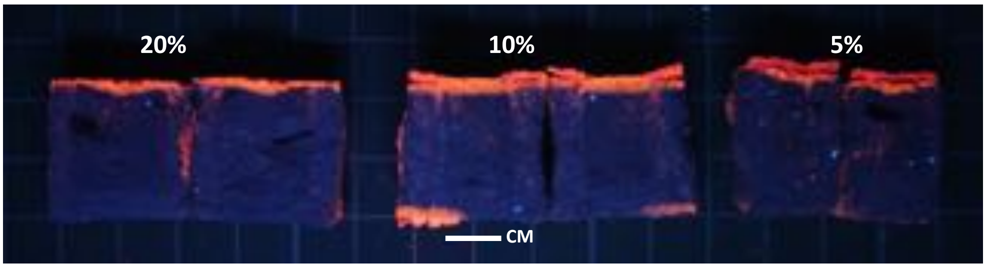


Figure 5.14 Analogue mudbrick samples consolidated with Primal B60A in stated concentrations with a fluorescent tagger. Notice the depth of fluorescence at slightly varying depths.

Due to the lack of conservation team continuity over the years and limited documentation of conservation treatments of the buildings, the concentration and application methods for the polymer varied greatly. By the time the treatment was eliminated in 2013, the polymer had been used in many buildings on open display across the site in concentrations ranging from 2.5% to 50%. Since the implementation of Primal AC-33 in the 1990s, the environment at the site has undergone significant changes with the construction of two permanent shelters over the South (2003) and North (2008) excavation areas.

In 2012 it became necessary to revise the suitability of this polymer system. Owing to the UNESCO World Heritage inscription, the aims for stabilization shifted from provisional to long term-display. Though long-term display was one of Hodder's project goals, it had not been the central priority of the conservation program. The ICOMOS recommendation generated the support for investigating a new conservation programme for the in-situ structures, and research into alternative methods began.

Furthermore, as site monitoring improved, specific deterioration patterns emerged, which correlated with the failure of the polymer rather than the archaeological substrate. The rising damp and microclimate created by the polymer film result in the surface coming away in sheets, this process mimics natural delamination but on a more substantial scale (Figure 5.15). Deterioration is chiefly coming from within the walls themselves. Rising damp within walls coupled with high levels of soluble salts resulting in wall under-cutting, plaster delamination, and surface erosion leading to collapse. This dilemma provided an interesting opportunity to review practices and challenge the adequacy of a methodology that is not unique to Çatalhöyük. With the data collected are part of the CDPP project locations of past and current intervention types can be monitored, and their effectiveness evaluated; though it should be noted that climate change seems to be a factor in treatment performance (Campanari et al. 2019).

Figure 5.15 Delamination due to ineffective consolidation and film formation at the base of a wall. The surface layers are coming away in plastic sheets, exposing the unconsolidated plaster underneath, which are then desiccating and powdering. Çatalhöyük, Building 5, Feature 230 (photograph by the author).

6 Method

6.1 Introduction

The following chapter outlines the methodological procedure used for the analytical work in this study. The procedures for sample preparation, Fourier Transform Infrared (FTIR) Micro-spectroscopy analysis, and Universal Testing Machine (UTM) procedure are presented. The focus of the analytical work is on the performance of mudbrick, as the substantive structural material of earthen architecture is the mudbrick fabric. For this reason, though archaeological samples of clay plaster are also examined in the FTIR analysis, plaster analysis is not cried through the other aspects of this research. While archaeological plasters can be a significant factor in the preservation of earthen structures, plasters are not always present pre- or post-excavation. With the in-situ preservation of earthen buildings as heritage structures mudbrick, in its various incarnations, is the core component that needs to be preserved.

Aim

To investigate the current knowledge gap regarding the outcome of consolidating earthen mudbrick substrates with aqueous acrylic dispersion systems.

Objectives

- Determine the penetration of a range of commonly used polymer systems into analogue mudbricks using FTIR Microscopy.
- Compare the outcomes of the polymer penetration studies with samples treated in situ with aqueous acrylic emulsions at the site of Çatalhöyük, Turkey.
- Use UTM testing equipment to investigate how surface application of polymer dispersions and solutions influences the strength of analogue mudbrick.
- Assess the strength of mudbrick analogues manufactured using polymer dispersions and solutions to investigate idealised consolidation outcomes.
- Correlate data and discuss the impact of this experimental study on perceptions of consolidation extant in conservation and the practice of consolidation in the field.

6.2 Archaeological and analogue samples

6.2.1 Archaeological Samples

During the 2015 and 2016 field seasons at Çatalhöyük, samples were taken from walls excavated and consolidated before 2012 (Figure 6.1). The purpose of taking pre-2012 samples was to obtain mudbrick treated with Primal (either AC-33 or B60A), which was phased out of architectural conservation at the site after this date. The conservation records for many of the buildings are sporadic before 2009, so sample areas were selected because they were 'likely' to have been consolidated. Thirty-one samples were taken from 10 buildings in the

North excavation area, 26 from 8 buildings in the South excavation area (Figures 5.3 and 5.4), and four samples from saved laboratory tests completed in 1996. Samples were taken in approximately 5cm x5cm x 2cm blocks whenever possible, to match samples produced in the laboratory. However, due to the friable nature of the material and poor handling during export and shipping, most samples were broken upon arrival in the Cardiff University laboratories.

Figure 6.1 Treatment history of Feature 1617 with Primal B60A. A. Çatalhöyük 2008, Primal B60A sprayed on to the archaeological surface (Photograph by Jason Quinlan). B. Sample from Feature 1617, composite sample of marl plaster and mudbrick, photograph taken after FTIR Multiscope analysis.

6.2.2 Mudbrick analogues

The analytical work for this study employs the use of both archaeological and laboratory-produced (analogue) mudbrick material. Using a composition similar to that identified in the mudbrick from Çatalhöyük (Love 2013; Matthews *et al.* 2013), an analogue mudbrick was created. This analogue composition provided standardization and reproducibility for analytical test procedures and is referred to as a **Laboratory Analogue** throughout this study. For selected tests, analogues were produced using ground up Çatalhöyük mudbrick and are referred to as **Çatalhöyük Analogue**. Actual mudbrick samples from the archaeological site at Çatalhöyük were also utilised to assess the impact of past in-situ consolidation processes carried out on-site.

Characterizing and duplicating original materials is an accepted methodology for experiments with earthen substrates. Recent research includes duplication of both original materials and methods, many of which involve modifiers (Oliver 2008). Tempers (organic/inorganic) have a long history of use in mudbrick formation, but because many of these materials decay, are lost or cannot be detected, information on their precise nature and use is often more anecdotal than factual, particularly when the tradition of using those materials has been lost (Love 2013). Tempers were not included in the analogue bricks as the archaeological bricks from Çatalhöyük only have impressions from where the tempers once were. While there are small voids, which naturally occur in the analogue sample making process, there is no practical way to recreate the voids in a standardized technique. Firing the test bricks to burn out the temper would chemically alter the clay. To ensure the analogues were as consistent as possible, limiting the variables created by adding tempers was a necessary conclusion.

6.2.3 Analogue production

The Laboratory Analogue mudbrick material is a mixture of 46% silt, 39% sand and 15% clay, compositionally similar to the mudbricks found at the Neolithic site of Çatalhöyük (Love 2013; Matthews et al. 2013). The Çatalhöyük bricks have a relatively low clay content (15%), whereas some mudbrick compositions can contain 60% clay (Velde 2008). The individual components for these test bricks were sourced as raw materials (Table 6.1), similar to Çatalhöyük back-swamp grade clay, which has a high iron content, aluminium, silicon and potassium (Table 6.2).

Table 6.1 Analogue mudbrick components and archaeological mudbrick morphology

Material and % v/v in analogue	Common name	Supplier	Morphology	Composition
Sand 39%	coarse silica	Bath Potters Supply	Angular to rounded aggregates of up approx. 300 µm	Si
Silt 46%	feldspar	Bath Potters Supply	Approx. 20 µm	Ca, Na, Al, Si
Clay 15%	AT Hymod Ball Clay	Bath Potters Supply	Approx. 2 µm	Al, Si, Fe, Mg, K

Table 6.2 Micromorphology of back-swamp clays at Çatalhöyük (Matthews et al. 2013).

Structure	Coarse fraction	Infrared	X-ray diffraction	Atomic absorption	X-ray fluorescence	Morphology	Elemental composition
Clay grade, massive matrix embedded with 10-20% silt to sand grade	Quartz, Feldspar, Bi-valve shell	Montmorillonite Calcite, Quartz	Quartz, Calcite, Kaolinite, Ferroan, dolomite	High iron concentration	High levels of aluminium, silicon, potassium and iron	Angular to rounded aggregates of 500–10 µm	Si with Al and Ca and some K, Mg and Fe

The dry ingredients were manually stirred for ten minutes to mix them. Water was then added to the soil mixture in the ratio of 15ml water per 100g of dry material. This ratio was established through multiple testing to be sufficient water for the bricks to be thoroughly mixed without the aggregates separating during drying (Table 6.3). The Laboratory Analogue mudbricks were cast in silicon formers measuring 5cm x 5cm x 2cm (Figure 6.2). They were removed after 48 hours, when they were robust enough to handle, then dried to constant mass (Mettler AJ100 balance ± 0.0001 g) in ambient laboratory conditions approximately 16-20°C, 35-45%RH for two weeks.

Table 6.3 Initial Test Mudbrick Water Ratio Tests

Composition	**Initial Observation**	**24 Hour Observations**	**Final Observations**
130g with 20ml deionised water	Just about damp enough, thick lumpy consistency, difficult to stir	Just past leather hard in the former. The brick has small gaps in the surface.	Brick has a consistent slightly pocked surface throughout.
130g with 30ml deionised water	Wet, slurry like consistency, a few small lumps present	Brick in the former is still pliable	Brick has sandy loam like surface, with the appearance of a fairly consistent fine texture. The surface that was face down in the former is smooth. The surface face up in the former appears to have a fine silt layer across the upper most surface.
130g with 40ml deionised water	Very Damp, almost slip like consistency, almost completely smooth	Brick in the former is still very damp and pliable	Brick has a sandier surface than the 30ml brick but has a smooth surface from the side face down in the former, and silt later on the opposite side. Bricks are slightly slumped and irregular at the sides.

Figure 6.2 Silicone formers for casting the analogue mudbricks.

The Çatalhöyük Analogue mudbricks were formed from Çatalhöyük material and fabricated using the same procedure as the Laboratory Analogues. Prior to their use to fabricate the analogues, Çatalhöyük mudbrick was subjected to FTIR analysis to ensure no polymers were present from on-site consolidation. The purpose of the Çatalhöyük Analogues was to confirm the data outputs from the Laboratory Analogues was similar to analogues produced using mudbrick from Çatalhöyük.

6.3 Fourier Transform Infrared Micro-spectroscopy Analysis

Mapping the depth of penetration of polymer into the mudbrick substrate was carried out using FTIR-microscopy. FTIR has been used to examine coatings and penetration depth in stone (Simionescu *et al.* 2011). FTIR-microscopy, mainly, facilitates the easy analysis of small samples and point-by-point mapping across a sample surface (Chalmers et al. 1996). Compression testing of earthen materials has long been established (Schroeder and Bieber 2004; Poggi 2006); however, the challenge for this study was to scale the experiments so that fluctuations in polymer performance could be detected in a manner that reflected field consolidation practices.

FTIR microscopy has been employed within conservation and cultural heritage to study pigments, binding media, varnishes, dyes, protective treatments and degradation products (Van't Hul-Ehrnreich 1970; Baker and Von Endt et al. 1988; Turner and Watkinson 1993;

Derrick 1995; Pilc and White 1995; Langley and Burnstock 1999; Paluszkiewicz and Dominik 2002; Joseph 2009). An FTIR microscope consists of an FTIR spectrometer combined with a specially designed optical microscope, which incorporates all-reflecting optics and aspherical surfaces adapted to infrared radiation. The infrared light source emits radiation directed to the microscope instead of the spectrometer's sample chamber (Joseph 2009). Results were acquired by external reflectance FTIR micro-spectroscopy using the Perkin-Elmer Multiscope™ System Microscope connected to the Perkin Elmer™ Spectrum One Spectrometer IR radiation source (Figure 6.3). The microscope is equipped with liquid nitrogen cooled MCT (Mercury, Cadmium and Telluride) detector. Reflectance spectra were collected after 20 scans, 4 cm-1 spectral resolution, 4000-600 cm-1 frequency range.

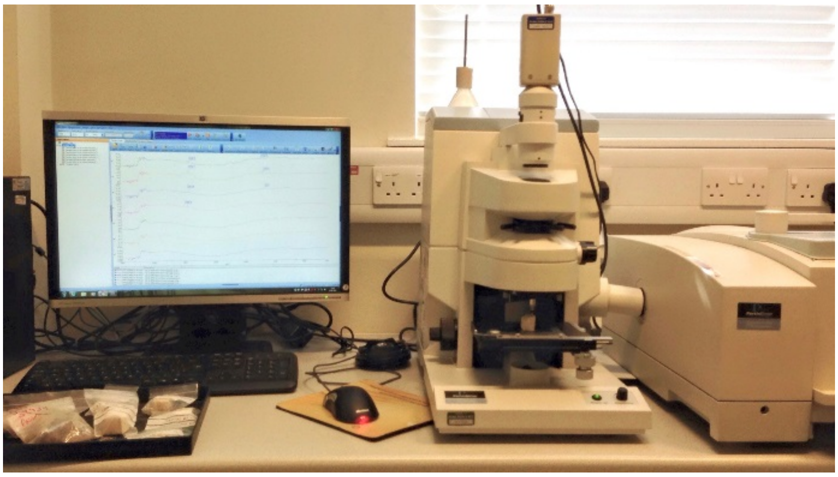


Figure 6.3 FTIR Perkin-Elmer Multiscope used in this experimental work.

Minor deviations can occur impacting on spectra quality when working with rough surface textures. Diffuse reflection spectroscopy (DRIFTS) occurs with a rough, porous, or powder sample, where the light is reflected at numerous angles that are not equal to the incident angle. The diffuse reflectance spectrum depends on sample density and refractive index, as well as on particle size and morphology, and may be displayed without any correction function (Derrick and Stulik 1999). The major problem that can occur with diffuse reflectance spectra is the inclusion of a strong specular reflection component that produces slight band distortions, such as slight shifts in absorption band position, and changes in relative band intensities (ibid).

An initial test series was carried out to determine whether the FTIR microscope was a suitable analytical tool for this study by establishing:

- whether it was possible to identify the presence of polymer in polymer/mudbrick mixtures by distinct diagnostic peaks;
- identifying low concentrations of polymer in Laboratory Analogues fabricated using polymer dispersions to determine limits of detection.

Spectra collected with the FTIR MultiScope were processed to correct the baseline and then were normalized so any real differences in sample reactivity could be determined (Derrick et al. 1999). Other corrective algorithms were not used because in some early tests they obscured the polymer peaks. Spectra were examined for the polymer and mudbrick alone. The use of FTIR to identify polymers is well established, a reference spectrum from Primal B60A was generated (Figure 6.4), further FTIR spectra produced at Cardiff for all polymers to be used in the tests, Primal AC-33, Acrysol WS-24, Paraloid B48N, Paraloid B44, and Paraloid B72 (Figures 6.5 to 6.9). Spectra were obtained for each component of the analogue mudbricks (Figure 6.10) by placing the raw material under the ATR (Attenuated total reflection) of the FTIR and a spectrum for the composite analogue material was also generated (Figure 6.11), along with and a spectrum for a Laboratory Analogue consolidated with 5% v/v Primal B60A diluted using deionized water (Figure 6.11). Reflectance spectra were collected after 20 scans, 4 cm^{-1} spectral resolution, 4000-600 cm^{-1} frequency range. The obtained energy gain (the reflected IR beam that returns to the detector) was noted for each spectrum before acquisition, and the Multiscope stage was adjusted (up or down) to have the highest energy gain possible from the sample surface.

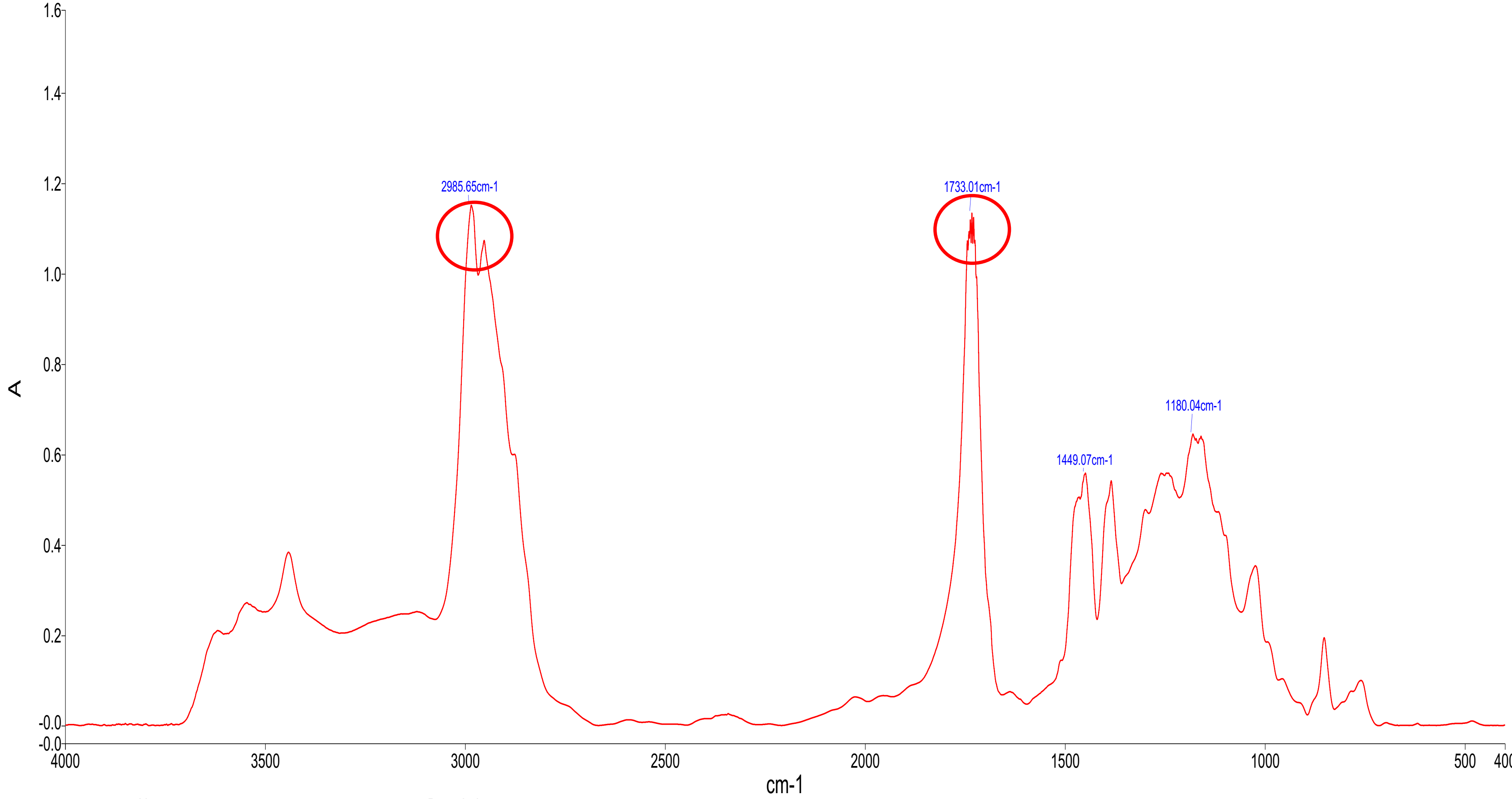


Figure 6.4 Spectra collected by FTIR Multiscope Primal B60A for this study. Distinctive peaks are present in the Alkanes Function Group 3000-2850 range, and another sharper peak in the Carbonyl Function Groups 1750-1720 range. Key peaks are circled in red.

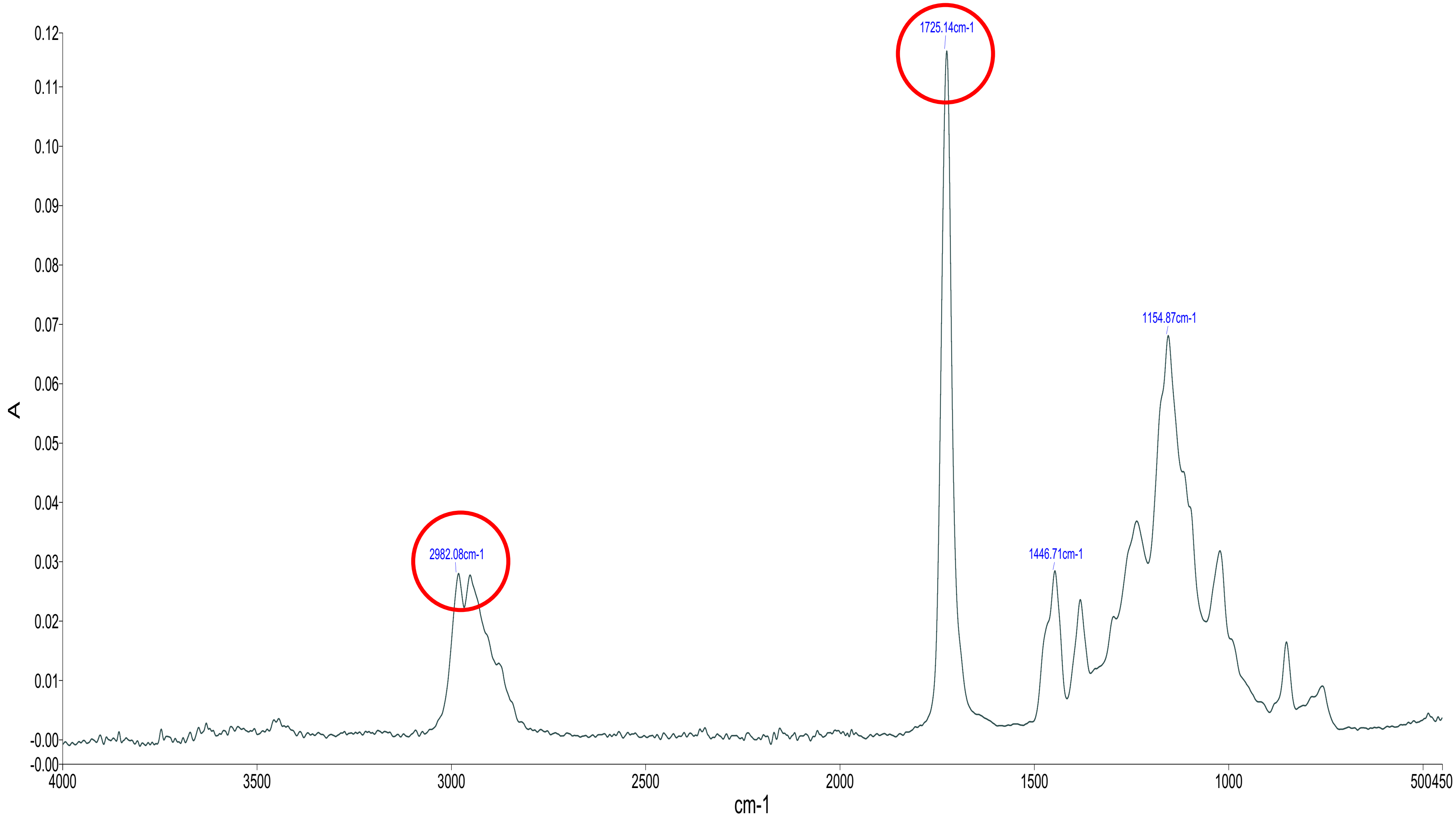


Figure 6.5 Spectra collected by FTIR Attenuated total reflection, Primal AC-33. Key peaks are circled in red.

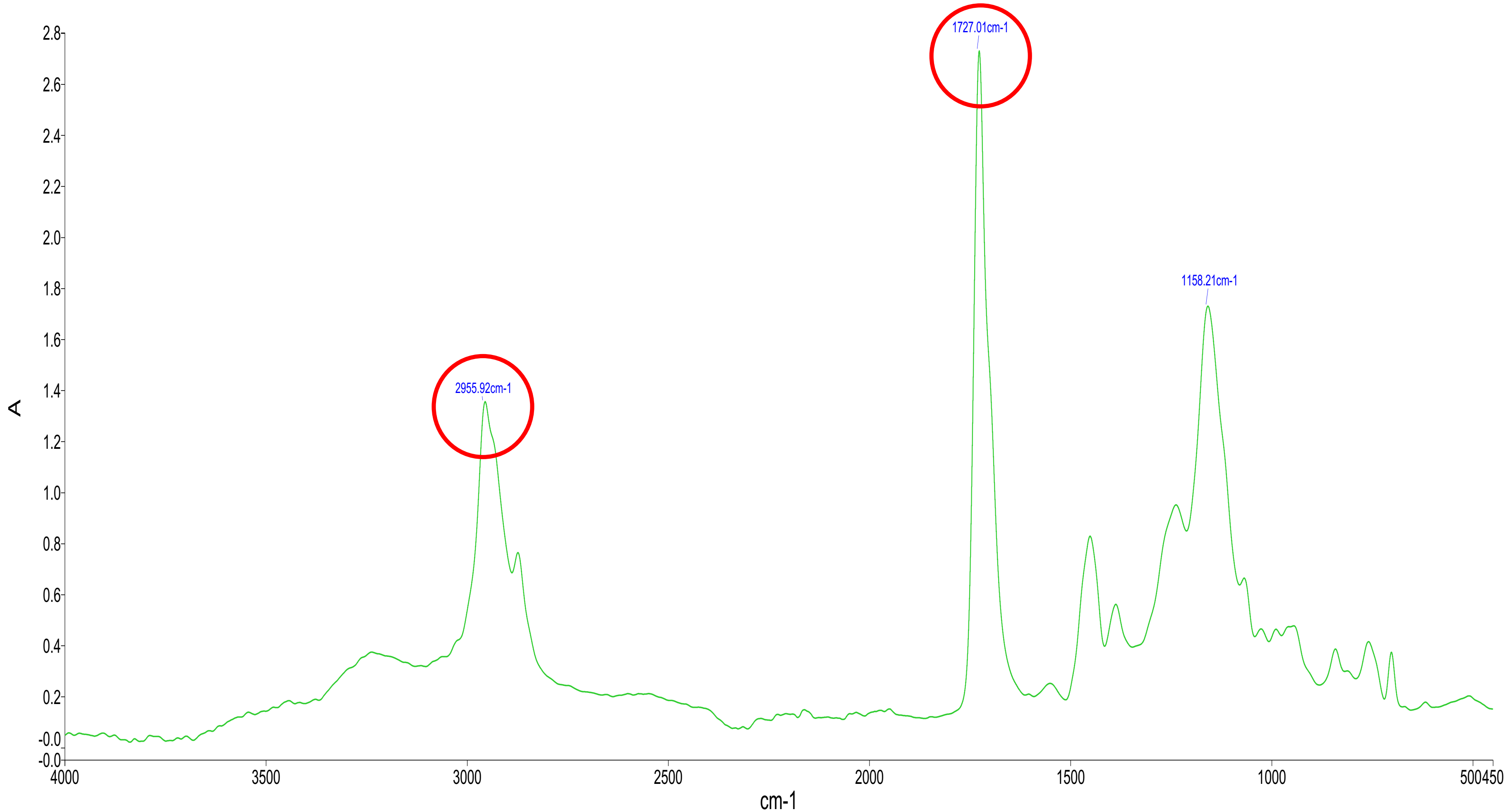


Figure 6.6 Spectra collected by FTIR Attenuated total reflection, Acrysol WS-24. Key peaks are circled in red.

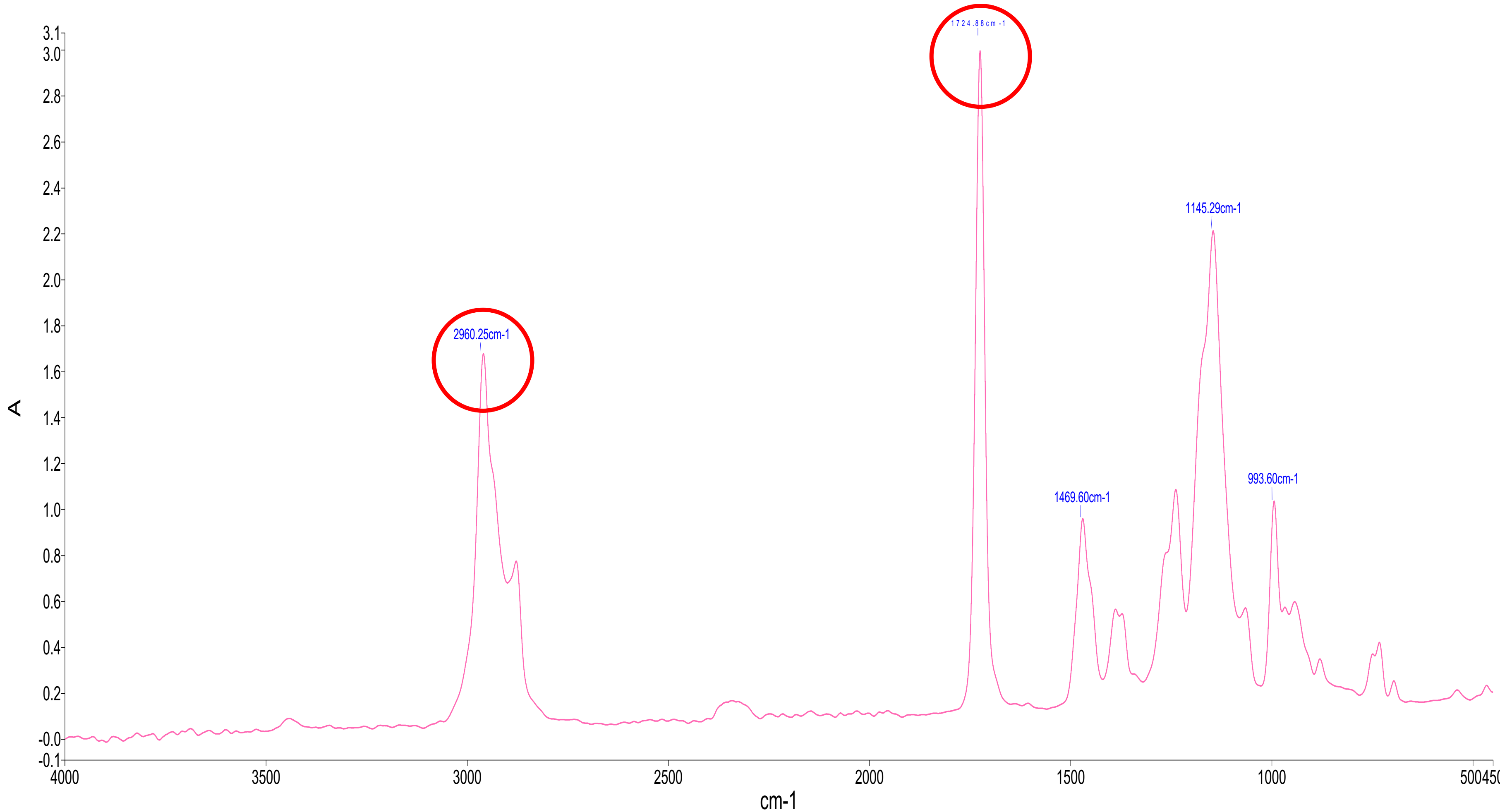


Figure 6.7 Spectra collected by FTIR Attenuated total reflection, Paraloid B48N. Key peaks are circled in red.

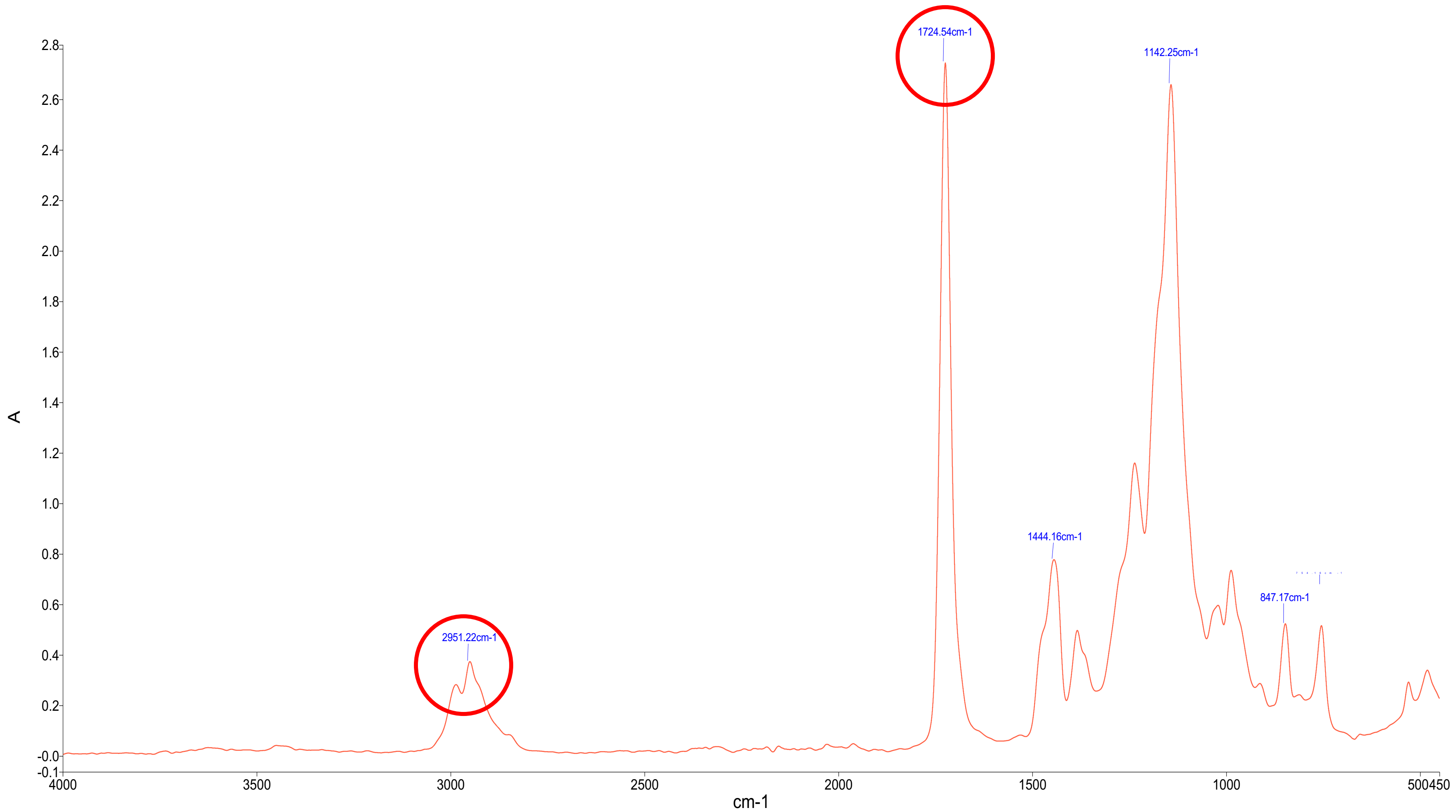


Figure 6.8 Spectra collected by FTIR Attenuated total reflection, Paraloid B44. Key peaks are circled in red.

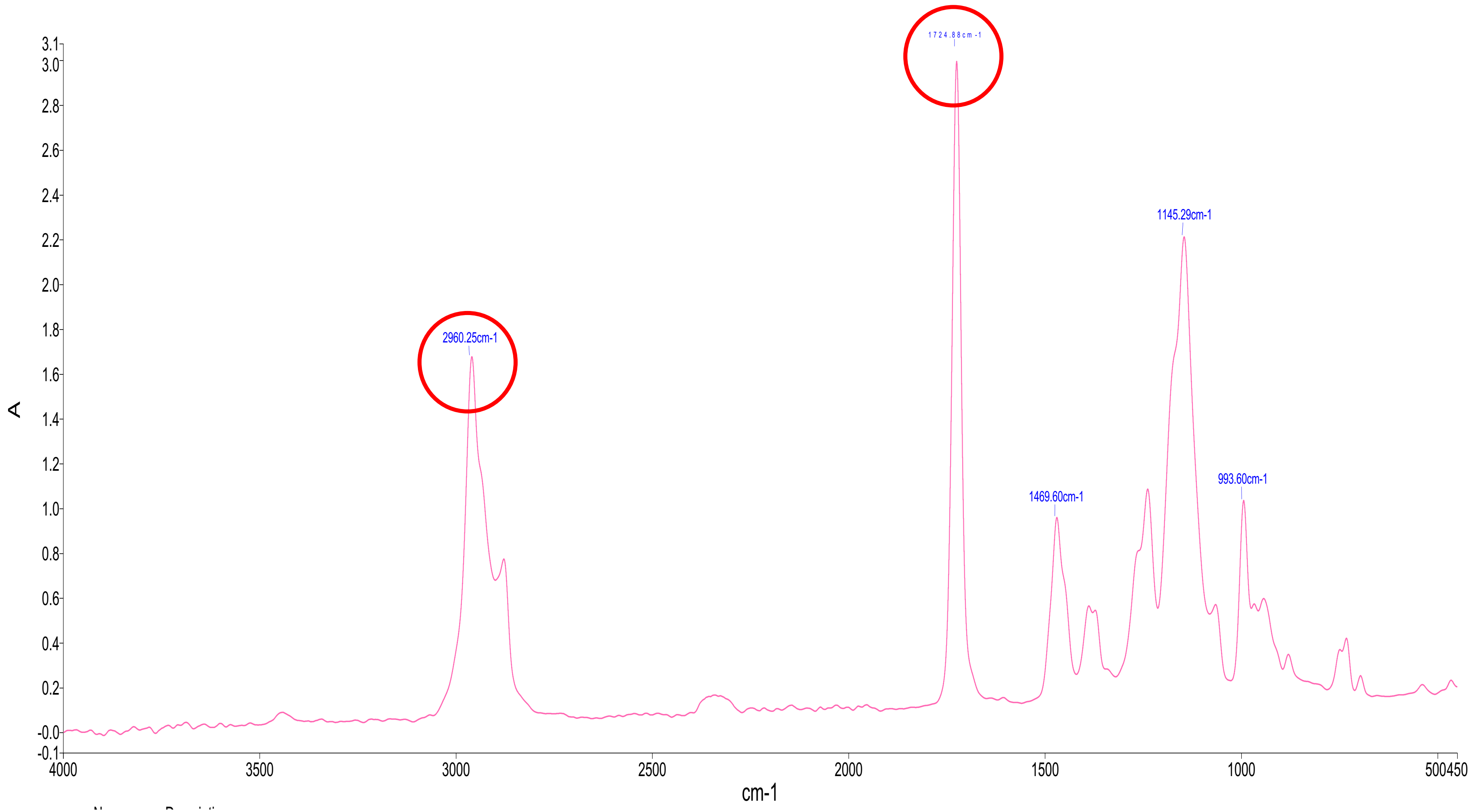


Figure 6.9 Spectra collected by FTIR Attenuated total reflection, Paraloid B72. Key peaks are circled in red.

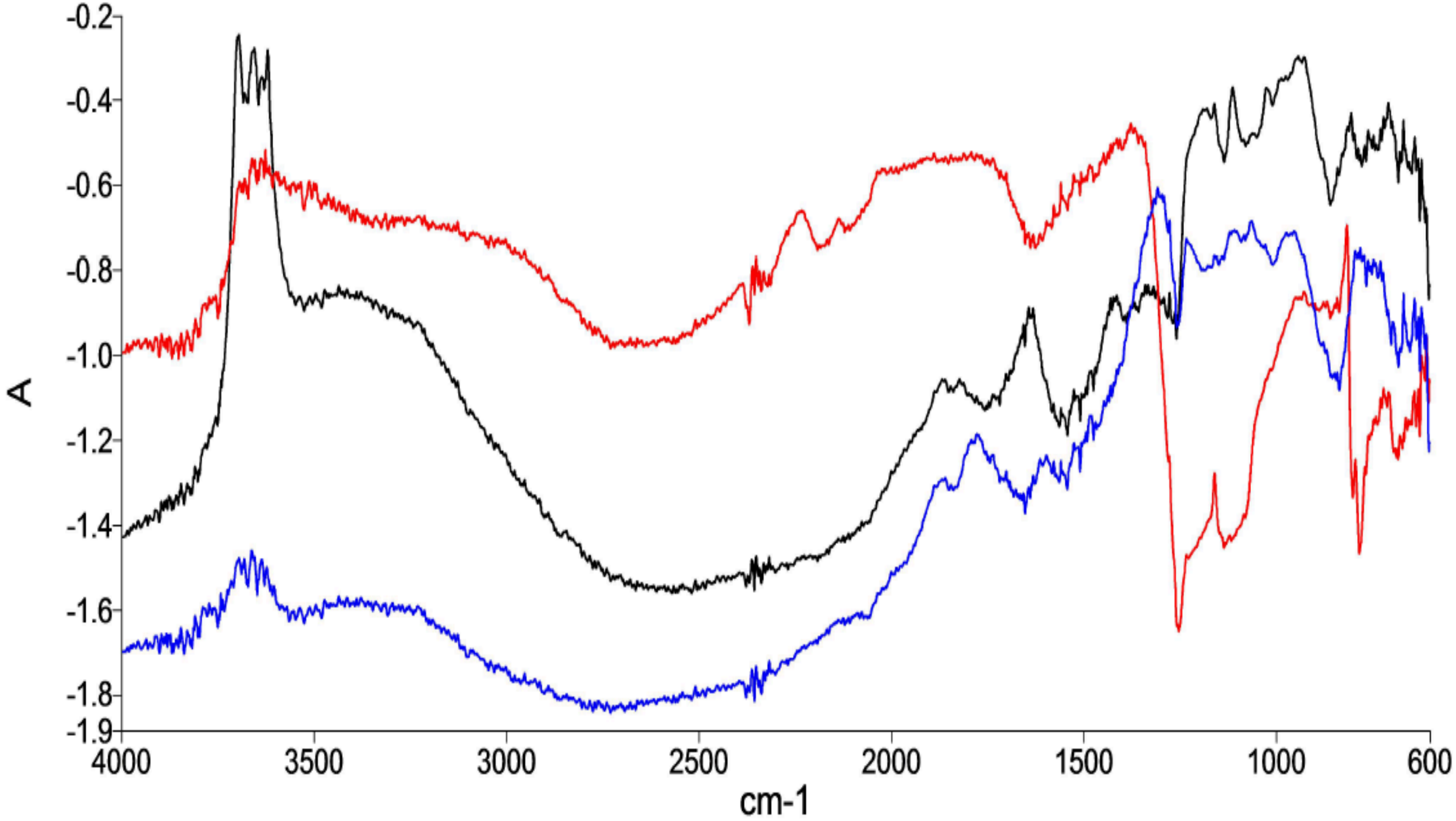


Figure 6.10 Individual components of Laboratory analogue mudbrick. Sand (red), silt (blue), clay (black).

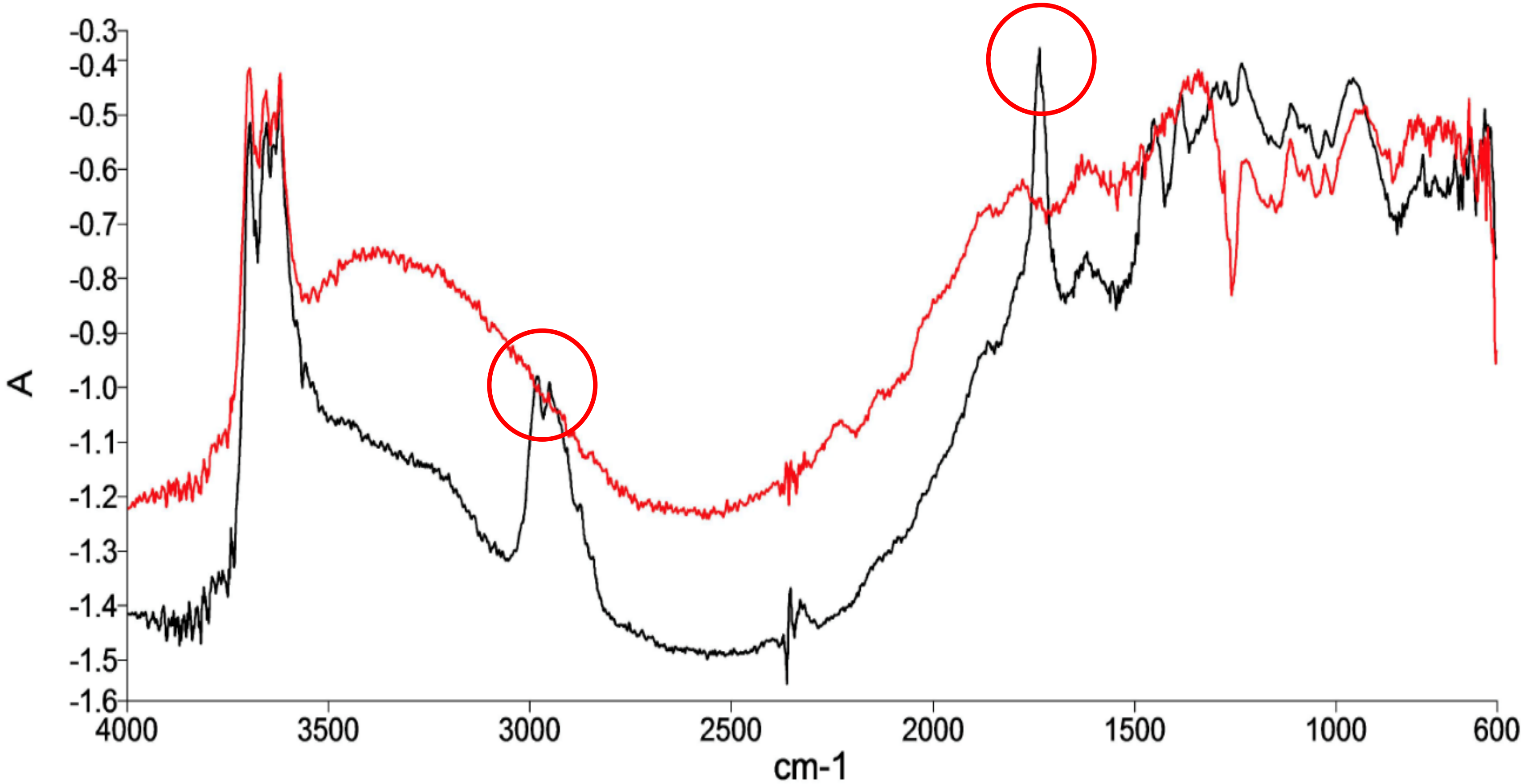


Figure 6.11 Sample surface spectrum. Analogue mudbrick spectra (red), analogue mudbrick spectra consolidated with 5% v/v Primal B60A in deionised water (black). The key peaks are circled in red.

The polymer is detected by peaks in the region *3000-2850* recording a range of C-H bonds and *1750-1720* representing the -C=O carbonyl groups (Figure 6.12) in the acrylic resin mixture of ethyl acrylate and methyl methacrylate. Due to the irregular nature of the mudbrick spectra as a composite, the fingerprint region of the spectra (from 1500 – 400 cm^{-1}) cannot be used in any part of this study. The characteristic peaks of the aqueous polymer in the region 1600 to 3800 cm^{-1} cannot be used diagnostically, as the FTIR is unable to differentiate between mudbrick and polymer in this region. The FTIR limit of detection for polymer in the Laboratory Analogue now needed to be established.

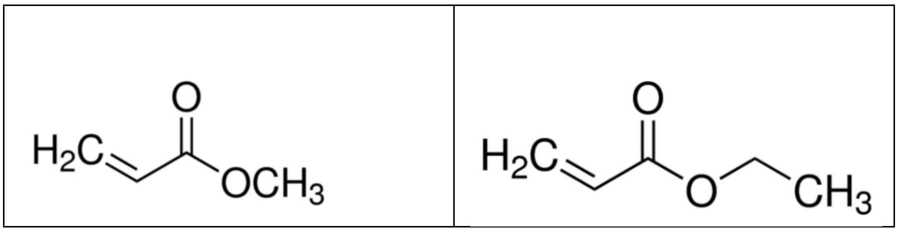


Figure 6.12 Methyl Acrylate and Ethyl acrylate monomers – characteristic bonds

6.3.1 Limits of detection of polymer in block

The limits of detection of polymer in the analogue earth matrix was determined by mixing specific concentrations of polymer dispersion Primal B60A, at fixed volume, with the same mass of earth matrix to create a single analogue (Table 6.4). This complete dispersal of the polymer within the mudbrick block matrix, reflects an idealised scenario where the polymer is evenly distributed throughout the block following consolidation. Primal B60A dispersion sold by the manufacturer contains 46.5% solids, comprising ethyl acrylate and methyl methacrylate, plus any other solids that are used to create the dispersion. This was diluted to 10% (4.65% solids) and 5% v/v (2.325% solids) with deionised water then incrementally diluted with deionised water until very small amounts of solids were present. To produce an individual analogue block, 30mls of Primal B60A concentration of each concentration in Table 6.4 was stirred manually into 130g of dry analogue matrix and dried to constant mass (Mettler AJ100 balance ± 0.0001 g).

Table 6.4 Concentration limits calibration full table of tests. Concentrations of Primal B60A (% dilution of original dispersion and % solids) mixed into the substrate.

Dilution Concentration B60A (%)	**Solids (%)**
10.00	4.65
7.50	3.49
5.00	2.33
3.75	1.74
2.50	1.16
1.88	0.87
1.25	0.58
0.94	0.44
0.63	0.29
0.47	0.22
0.31	0.15
0.23	0.11
0.16	0.07
0.12	0.05
0.08	0.04
0.06	0.03
0.04	0.02
0.03	0.01

The analogue blocks were scored along their sides and bottom then snapped. This cross-sectional preparation process was tested several times to ensure there was reproducibility. The FTIR Multiscope microscope was used to collect spectra from the surface of the analogue blocks and the centre of their snapped cross sections. The Multiscope microscope has a field of view 600mm (x-axis) x 400mm (y-axis) and the IR beam was aligned in the centre of this field with a beam size of 0.25mm. Once the sample is in position, the Multiscope is switched to the Reflectance setting. By collecting spectra from the surface and centre of the block, it was possible to determine whether there had been chromatographic movement of the polymer towards the surface of the analogue block during drying. If it had not occurred, the polymer should be detected both on the surface and in the core of the analogue block, supporting the concept of even distribution of polymer within the mix.

6.3.2 Consolidation practice in the field using Primal B60A

To replicate how earthen surfaces are often consolidated in the field with Primal B60A, Laboratory Analogue samples were impregnated with 5mls of Primal B60A 25% v/v or 10% or 5% in deionised water and dried in ambient laboratory environment to constant mass (Mettler AJ100 balance ± 0.0001g). To test reproducibility of the consolidation process and its outcome, four samples were produced for each concentration. Unless otherwise stated, all samples were consolidated while they were horizontal by pipetting onto the centre of their largest surface area (Figure 6.13). This position offers maximum potential for the polymer to disperse into the sample surface and replicates idealized field practice when applying polymer dispersions to horizontal surfaces. The polymer dispersion was spread dropwise on the surface, allowing surface tension to pull the polymer towards the edges. Using a graduated pipette, 5mls of a Primal B60A dispersion was applied. This volume was the maximum that would sit on the surface without running over the edge of the block, yet it sufficiently saturated the surface. The consolidant dried in ambient laboratory conditions unless otherwise stated.

Figure 6.13 Laboratory Analogue mudbrick post-consolidant application. 5mls of 5% Primal B60A v/v in deionized water drying in ambient laboratory conditions. The smooth edge is due to the silicon former and does not represent the texture of the block interior (see Figure 6.2)

To examine how far the polymer migrated into the samples, the bricks were scored along their sides and bottom then snapped, leaving the consolidated surface untouched. Snapping the sample avoided any redistribution of the polymer or analogue mudbrick components that curing would cause. Analysis involved taking FTIR spectra of the horizontally consolidated surface of the sample brick (Figure 6.14). From there the sample was rotated 45° to expose the snapped edge, scans were taken at the break edge, excluding the distinctly visible consolidant layer, then spectra were collected using the Multiscope with a beam size of 0.25mm, across the snapped edge at 1 mm intervals moving inwards towards the block centre measured by the graduated adjustable stage of the microscope. Spectra were taken twice at 1mm intervals making 16 measurements per concentration.

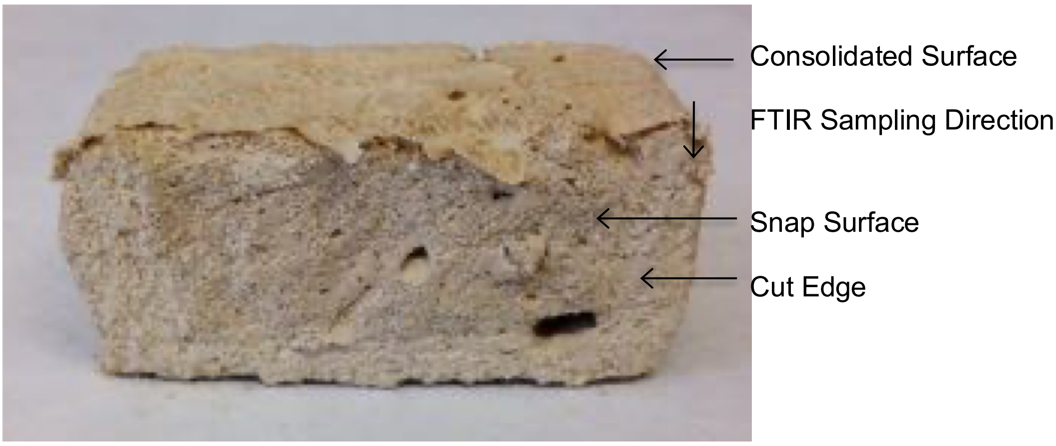


Figure 6.14 Cross section preparation of surface consolidated Laboratory Analogues for the multiscope.

6.3.3 Assessing consolidants commonly used in field practice

To compare the depth of penetration of other commonly used consolidants to Primal B60A, Laboratory Analogue tests were run with a range of polymer systems using the same application strategy. These polymers were chosen based on their applications in conservation practice and were applied in concentrations that reflect their common usage (Table 6.5). Often climate influences the use of polymer by temperature and humidity impacting on evaporation and drying times.

Table 6.5 Polymer systems applied to Laboratory Analogues

Polymer consolidation system	Rationale
Primal AC-33 (aqueous acrylic emulsion) 5% v/v in deionised water	Predecessor of Primal B60A.
Acrysol WS-24 (aqueous acrylic colloidal dispersion)	Used for mudbrick consolidation
Paraloid B48N (thermoplastic acrylic resin) 5% and 10% w/v in acetone	Popular polymers for use on sites in hot climates.
Paraloid B44 (thermoplastic acrylic resin) 5% and 10% w/v in acetone	Popular polymers for use on sites in hot climates.
Paraloid B72 (thermoplastic acrylic resin) 5% and 10% w/v in acetone	Commonly used in the consolidation of wall plasters.

6.3.4 Distribution of polymer in consolidated Çatalhöyük mudbrick samples

Çatalhöyük archaeological samples were selected where their original surface was still intact. These were snapped in half to expose a fresh break for scanning without pre-snapping scoring, as this was unnecessary due to their friability (Figure 6.15). FTIR spectra were first collected on the consolidated outer surface of the sample brick then the sample was rotated 45° to expose the snapped edge, scans were taken at the break-edge excluding the distinctly visible consolidant layer, then scanned at the break-edge, 1mm below the surface, and 5mm below the surface. These distances were selected to look for consolidation having taken place, beyond just surface film formation.

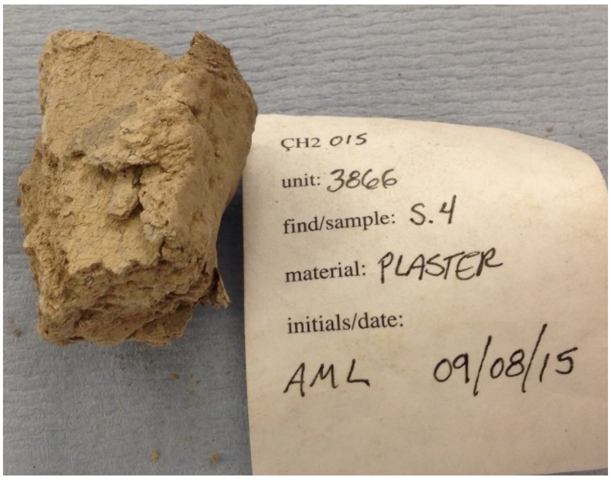


Figure 6.15 Archaeological sample collected from Çatalhöyük, Feature 230, Building 5. This particular sample is of clay marl, from a wall that had documentation of consolidation treatment with Primal B60A multiple times from 2004 to 2011 in varying concentrations (Appendix).

6.3.5 Çatalhöyük Analogues

Two Çatalhöyük Analogue mudbricks were made using Çatalhöyük mudbrick that had been analysed to confirm the absence of polymer. The mixture materials were drawn from a selection of site samples from a range of stratigraphic contexts to account for material variability (variations in clay/sand/silt) and to ensure these fabricated samples were representative of the site. Approximately 260g of this Çatalhöyük mudbrick was dry ground with a mortar and pestle until it had a similar texture to the ingredients used to make the laboratory analogues. The Çatalhöyük Analogues were made in the silicon formers used for fabricating Laboratory Analogues and dried to constant mass (Mettler AJ100 balance ± 0.0001 g). These were consolidated using the same protocol as the laboratory analogues, which consisted consolidation with 5mls of 5% Primal B60A v/v in deionized water followed by drying in ambient laboratory conditions.

6.4 Universal Testing Machine Analysis

The impact of applying selected synthetic carbon-based polymer systems on the physical properties of an earthen substrate was examined using a Zwick/Roell Universal Testing Machine (UTM) (error ±0.01%) (Figure 7.8A). This measures the tensile or compressive strength of materials (Callister and Rethwisch 2012). It is constructed of a load frame with a hydraulic crosshead, while a load cell measures the force necessary to cause deformation in the sample. The resulting stress-strain curve measures the amount of force (Newton) over the amount of deformation (millimetres), providing insight into material elasticity and the final rupture point at which the material irreparably breaks. With UTM testing, a sample is vertically compressed without limitations to the lateral expansion. This position mimics the same type of load-bearing stress an archaeological earthen wall would face. Meaning, the fabricated samples could be treated on a single surface, placed vertically in the machine, as one would find a consolidated mudbrick in the field.

Compression testing has been used to study consolidation of mudbrick in other mudbrick contexts. Coffman et al. (1990) discuss the use of compression testing for the consolidant applied in the Fort Selden research. Their research identified that clay type in adobe composition plays a significate factor in strengthening when working with isocyanate and alkoxysilane consolidants. Lee et al. (2009) combined compression testing with environmental modelling to determine the effectiveness of ethyl-silicate systems in the treatment of mudbrick.

6.4.1 Experimental Method UTM

The compressive strength of Laboratory Analogue samples consolidated with selected polymer solutions/dispersions, were compared to Laboratory Analogue samples produced by fully integrating the polymer into the liquid phase used in the Laboratory Analogue formation process. The rationale for each of the 12 test groups is provided in Table 6.6. 120 Analogue samples were produced for this experiment comprising 10 analogues in each sample group of the 12 test groups. All Analogues were dried in ambient laboratory conditions except for four sample groups, that were consolidated and dried in conditions equating to climates representing Arid 50°C/25% RH, Tropical 40°C/90%RH, Temperate 10°C/75%RH (autumn/winter) and Continental 10°C/25%RH (autumn/winter). The climatic chamber used for relative humidity and temperature controlled drying procedures was a Binder KBF-240V, with a Sartorius Quintix 125D analytical balance (± 0.00001 g) to assess end point as constant weight. Samples for the environmental curing groups were first conditioned for twelve hours in the designated environment, at the end of which 5mls of 5% Primal B60A v/v in deionized water was applied and allowed to dry for a further twelve hours in the same environment that the Analogue block was conditioned. For storage and transportation to the UTM facility, these environment consolidated Analogues were stored in Stewart Plastics boxes containing silica gel conditioned to their drying environment.

Table 6.6 Sample groups for UTM tests

Sample Group	Notation	% and mass of polymer solids (per block) and volume of dilution	Description	Purpose
1	Mix5%	2.33% / 30mls 0.70g	5% Primal B60A v/v in deionized water is fully incorporated into the substrate during manufacture of the mudbrick	Represents ideally consolidated mudbricks
2	Mix15%	6.98% / 30mls 2.09g	15% Primal B60A v/v in deionized water is fully incorporated into the substrate during manufacture of the mudbrick	Represents ideally consolidated mudbricks
3	AP5%	2.33% / 9mls 0.21g	5% Primal B60A v/v in deionized water. This delivers the same mass of polymer as is applied to Sample Group 4. Applied to the mudbrick via its surface with controlled variables.	Equal amounts of polymer applied to the surface of the analogues. A 15% dilution of Primal B60A has a solids content of 6.9% three times that of a 5% dilution, thus the sample groups 3 and 4 have a 1:3 ratio
4	AP15%	6.98% / 3mls 0.21g	15% Primal B60A v/v in deionized water an equal amount of polymer to Sample Group 3 applied to the mudbrick via its surface with controlled variables.	Equal amounts of polymer applied to the surface of the analogues. A 15% dilution of Primal B60A has a solids content of 6.9% three times that of a 5% dilution, thus sample groups 3 and 4 have a 1:3 ratio
5	AS5%	2.33% / 5mls 0.12g	5% Primal B60A v/v in deionized water an equal amount of dilution to Sample Group 6.	Same volume of consolidant with different concentrations of polymer solids.
6	AS15%	6.98% / 5mls 0.35g	5% Primal B60A v/v in deionized water an	Same volume of consolidant with

			equal amount of dilution to Sample Group 5.	different concentrations.
7	50_25	2.33% / 5mls 0.21g	Arid climate prepared at 50°C and 25% RH. 5% Primal B60A v/v in deionized water.	To examine the environmental impact on drying relative to compressive strength.
8	40_90	2.33% / 5mls 0.21g	Tropical climate prepared at 40°C and 90%RH. 5% Primal B60A v/v in deionized water.	To examine the environmental impact on drying relative to compressive strength.
9	10_75	2.33% / 5mls 0.21g	Temperate climate prepared at 10°C and 75%RH. 5% Primal B60A v/v in deionized water.	To examine the environmental impact on drying relative to compressive strength.
10	10_25	2.33% / 5mls 0.21g	Continental climates prepared at 10°C and 25%RH. 5% Primal B60A v/v in deionized water.	To examine the environmental impact on drying relative to compressive strength.
11	UT	-	No polymer application, untreated.	For comparative reference.
12	PB44	5mls of 5% w/v in acetone	Solvent Based system: 5% Paraloid B44 w/v in acetone.	For comparative reference.

The samples were loaded vertically into the machine with the flattest side on the stationary block. A piece of Sundeala board was placed between the upper part of the sample and the load cell (Figure 6.16). The machine was set to begin recording deformation at 20 Newton to account for the additional board with a compression rate of 3mm per minute. Tests were discontinued once the bricks had passed the point of rupture, noted as 'Fmax' in the UTM data report. Max value is recorded for the force (N) and deformation (mm) caused by the compression of each sample. The tests performed for this experiment were carried out in ambient laboratory conditions.

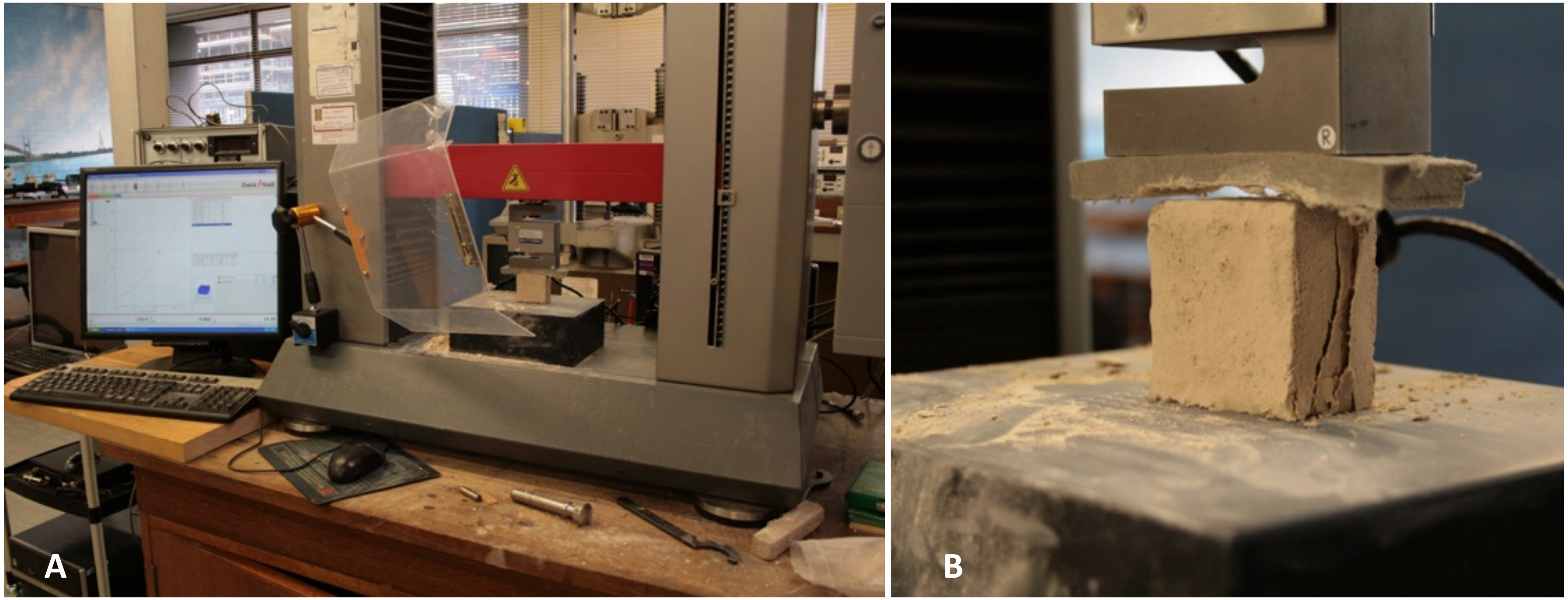


Figure 6.16 UTM compression process. A. UTM set-up during compression of Laboratory Analogue mudbrick. B. Sample post compression

7 Results

7.1 FTIR limit of detection of polymer in a Laboratory Analogue

Table 7.1 gives the result of the concentration limits testing carried out by producing Lab Analogues fabricated with differing concentrations of Primal B60A. Figure 8.1 provides selected FTIR spectra used to construct Table 7.1. Full spectra at a higher printed resolution making it easier to identify the disappearance of characteristic peaks are available in the Appendix.

Table 7.1 Concentration limits calibration.

Primal B60A Concentration v/v used to produce Lab Analogue (%)	Solids (%)	FTIR Characteristic Peak Detection B60A
10.00	4.65	Yes
7.50	3.49	Yes
5.00	2.33	Yes
3.75	1.74	Yes
2.50	1.16	Yes
1.88	0.87	Yes
1.25	0.58	Yes
0.94	0.44	Yes
0.63	0.29	Yes
0.47	0.22	Yes
0.31	0.15	Yes
0.23	0.11	Yes
0.16	0.07	Yes
0.12	0.05	No
0.08	0.04	No
0.06	0.03	No
0.04	0.02	No
0.03	0.01	No

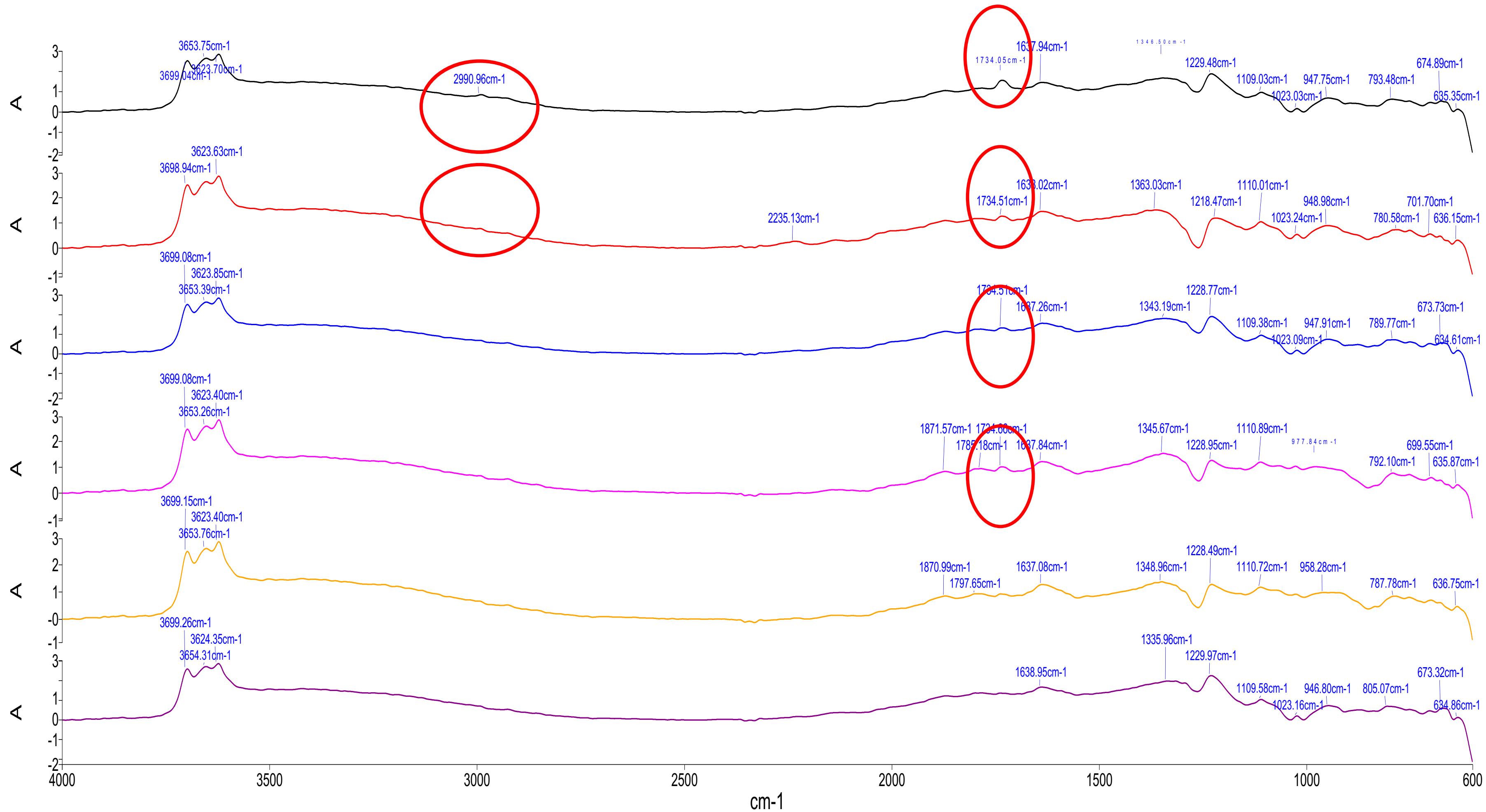


Figure 7.1 FTIR spectra from selected concentration limits calibration tests. In descending order Primal B60A mixed within an analogue mudbrick in: 5% (Black), 2.5% (red), 1.25% (blue), 0.156% (pink), 0.117% (yellow), 0.078% (purple) dilutions. Polymer peaks are circled in red.

7.2 Consolidation in conservation field practice

7.2.1 Laboratory Analogues

Results of tests examining the penetration of other aqueous and solvent based polymer systems used for consolidation of mudbrick in conservation practice are reported in Table 7.2 and in Figures 7.2 to 7.13.

Table 7.2 Polymers, solutions, and concentrations

Material	Particle Size	Solids (Dispersion)	Continuous phase or Solvent	Concentration	Results (FTIR limit of detection)
Primal AC-33	0.1µm	46%	Water	5% v/v	horizontal surface
Acrysol WS-24	0.03µm	36%	Water	10% v/v	horizontal surface
Acrysol WS-24	0.03µm	36%	Water	20% v/v	horizontal surface
Paraloid B48N			Acetone	5% w/v	1mm below the horizontal surface
Paraloid B48N			Acetone	10% w/v	horizontal surface
Paraloid B44			Acetone	5% w/v	1mm below the horizontal surface
Paraloid B44			Acetone	10% w/v	horizontal surface
Paraloid B72			Acetone	5% w/v	1mm below the horizontal surface
Paraloid B72			Acetone	10% w/v	horizontal surface
Primal B60A	0.03µm	46.5%	Water	5%	horizontal surface
Primal B60A	0.03µm	46.5%	Water	10%	horizontal surface
Primal B60A	0.03µm	46.5%	Water	25%	horizontal surface

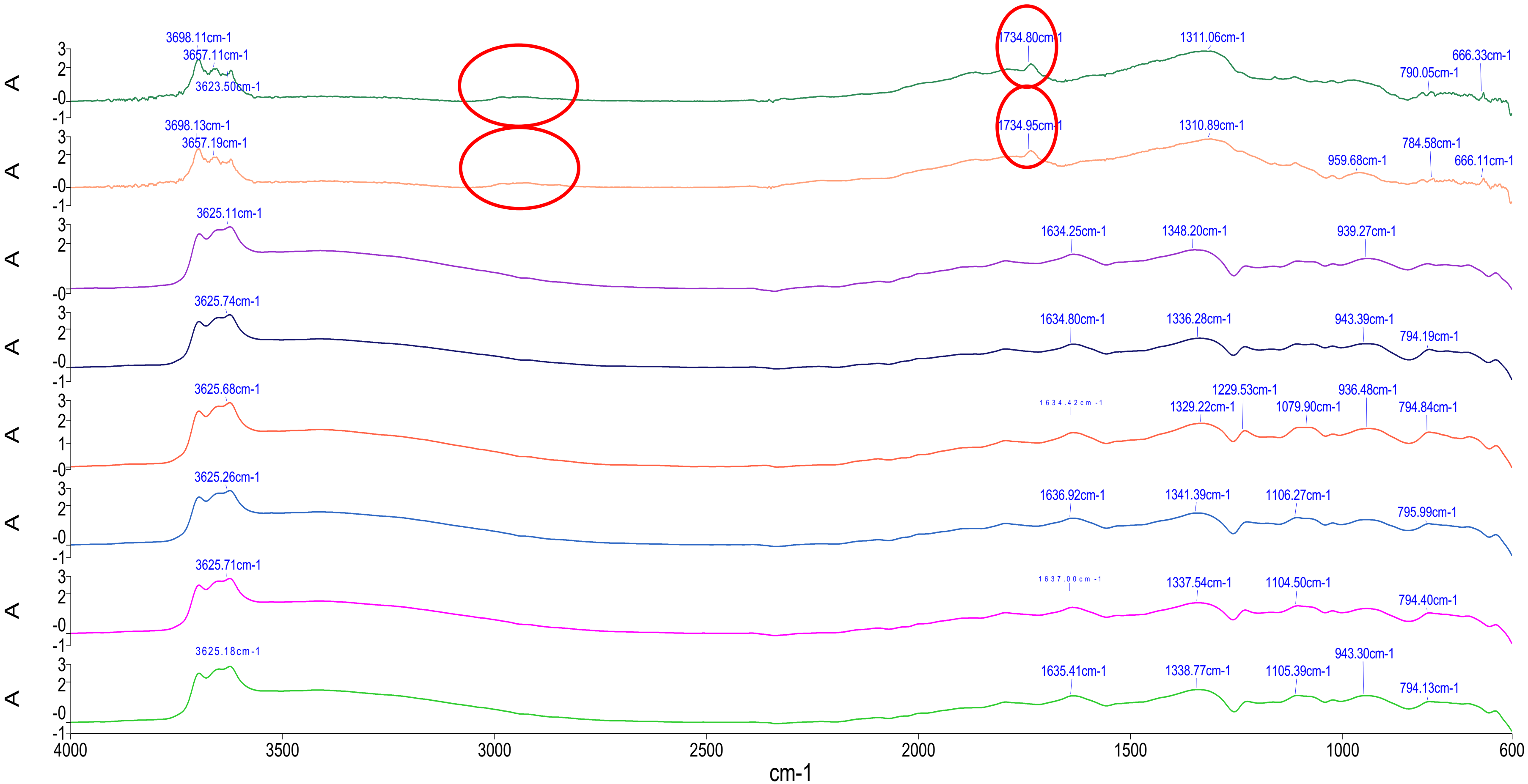


Figure 7.2 Spectra collected by FTIR Multiscope, cross-section analysis. 5% Primal AC-33 5% v/v in deionised water. Two scans per location, in descending order: surface (green and orange); break edge (purple and navy); 1mm depth (orange and blue); 5mm depth (pink and lime). Diagnostic peaks indicating the presence of polymer circled in red.

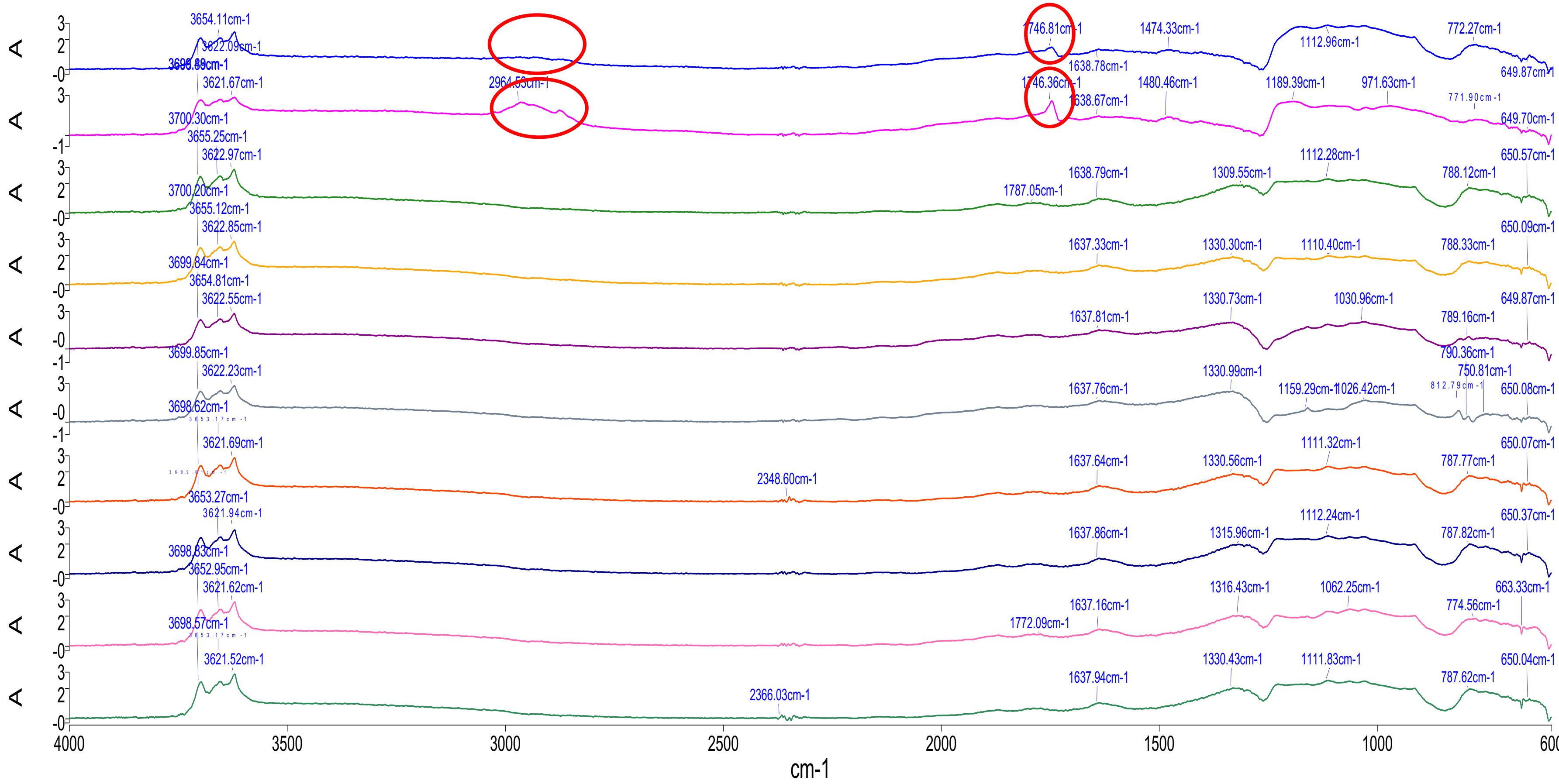


Figure 7.3 Spectra collected by FTIR Multiscope, cross-section analysis. 10% Acrysol WS-24 v/v in deionised water. Two scans per location, in descending order: surface (blue and pink); break edge (green and yellow); 1mm depth (purple and grey); 2mm depth (orange and navy); 5mm depth (pink and green). Diagnostic peaks indicating the presence of polymer circled in red.

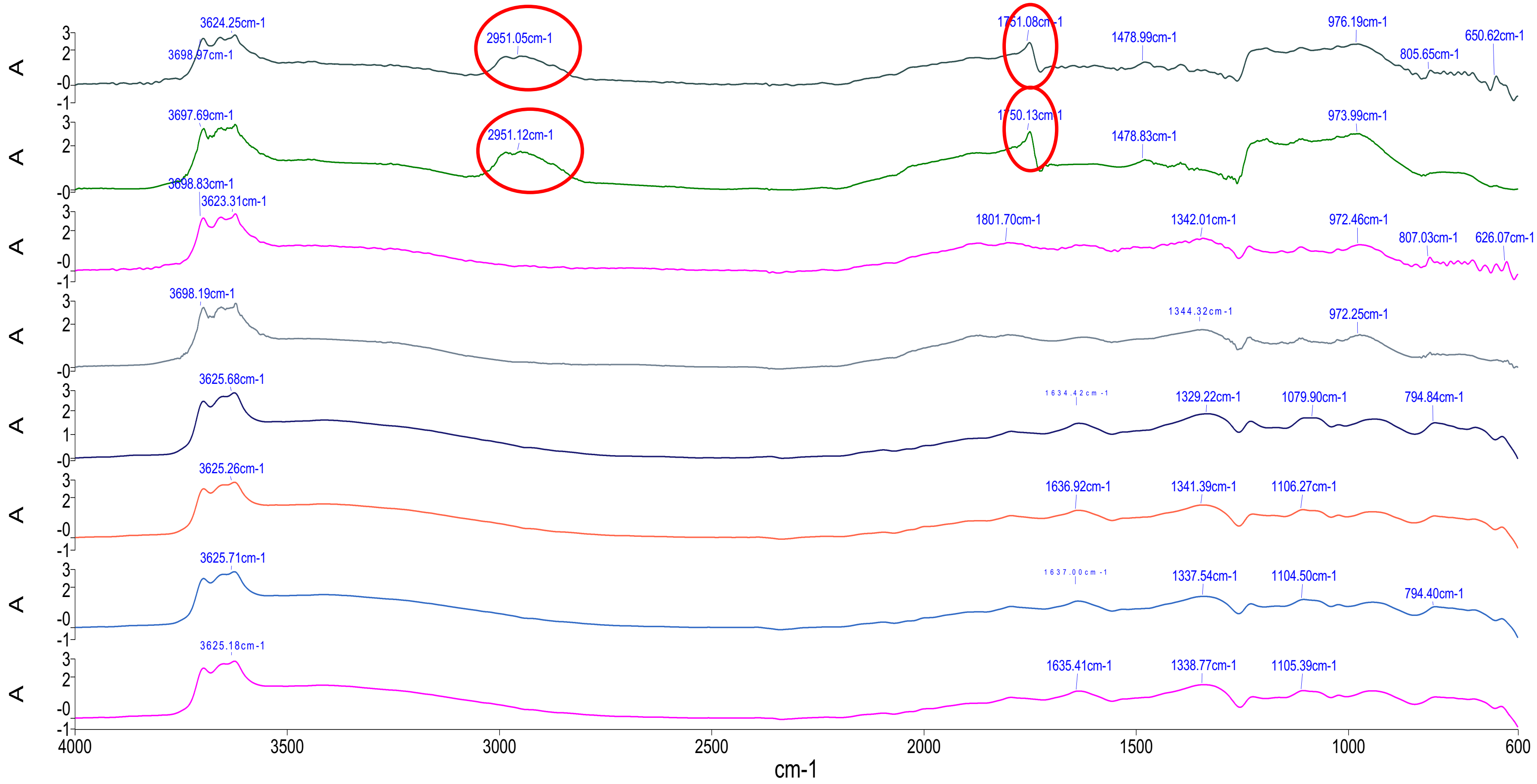


Figure 7.4 Spectra collected by FTIR Multiscope, cross-section analysis. 20% Acrysol WS-24 v/v in deionised water. Two scans per location, in descending order: surface (grey and green); break edge (pink and grey); 1mm depth (navy and orange); 5mm depth (blue and pink). Diagnostic peaks indicating the presence of polymer circled in red.

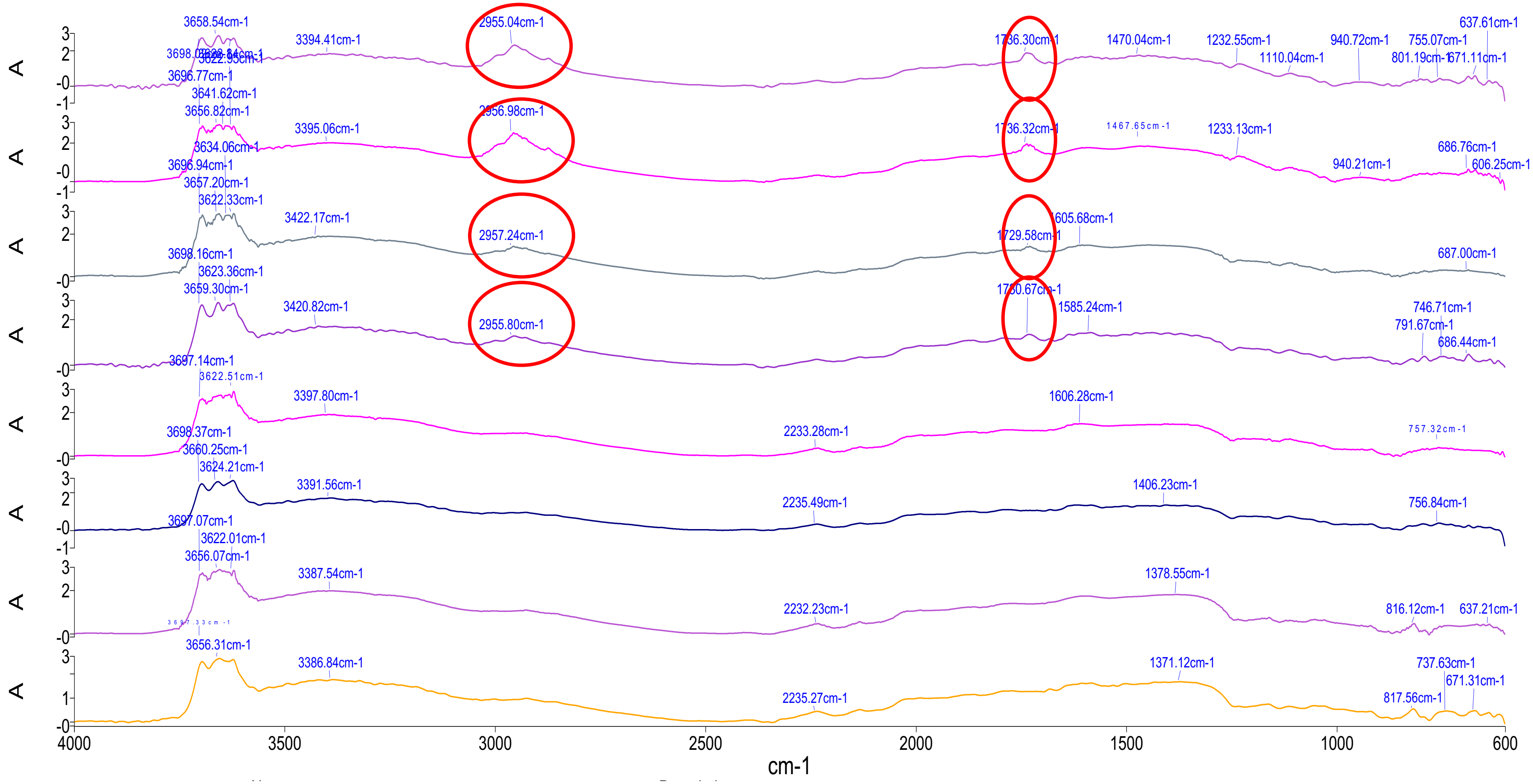


Figure 7.5 Spectra collected by FTIR Multiscope, cross-section analysis. 5% Paraloid B48N w/v in acetone. Two scans per location, in descending order: surface (purple and pink); break edge (grey and purple); 1mm depth (pink and navy); 5mm depth (purple and yellow). Diagnostic peaks indicating the presence of polymer circled in red.

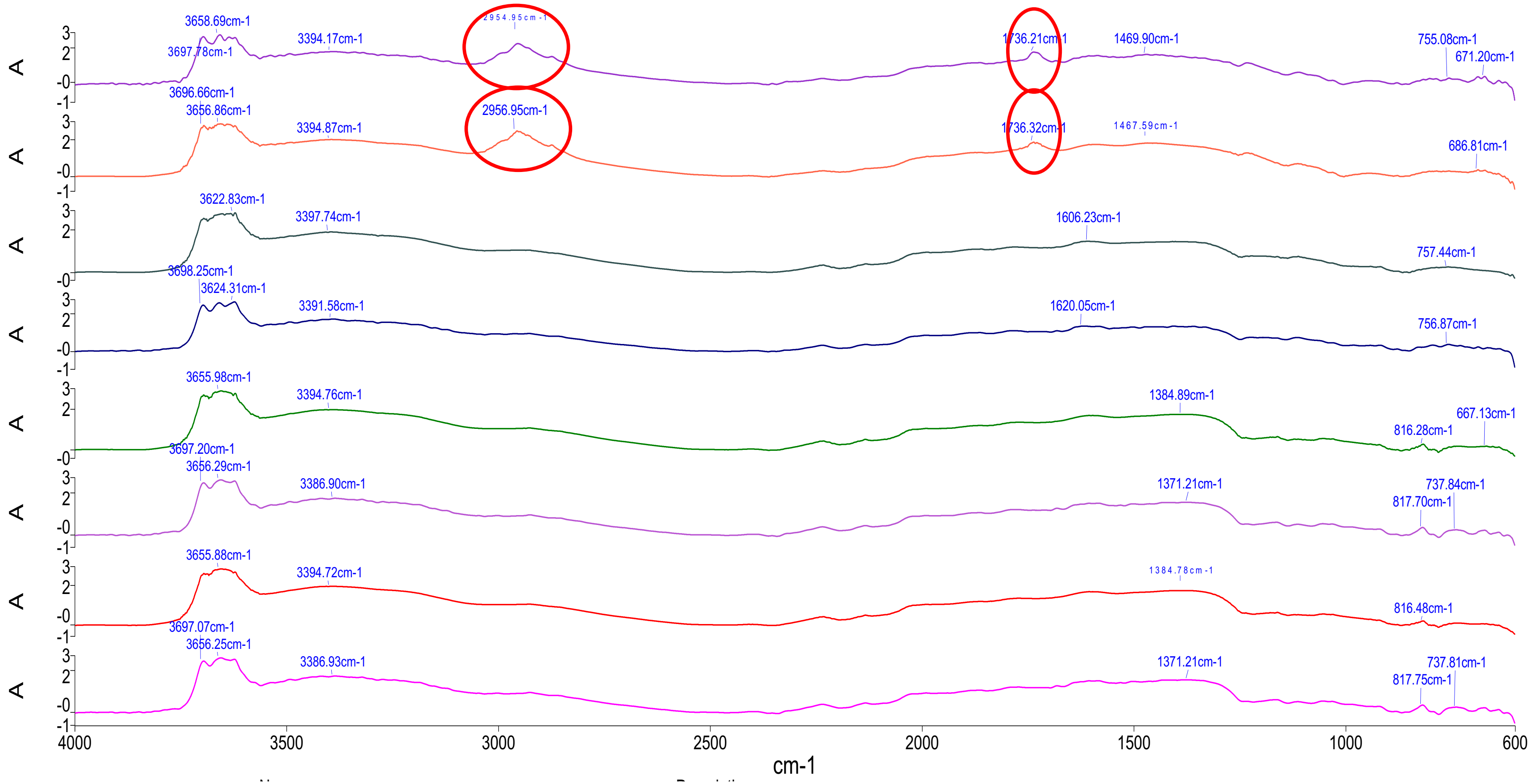


Figure 7.6 Spectra collected by FTIR Multiscope, cross-section analysis. 10% Paraloid B48N w/v in acetone. Two scans per location, in descending order: surface (purple and orange); break edge (grey and navy); 1mm depth (green and purple); 5mm depth (red and pink). Diagnostic peaks indicating the presence of polymer circled in red.

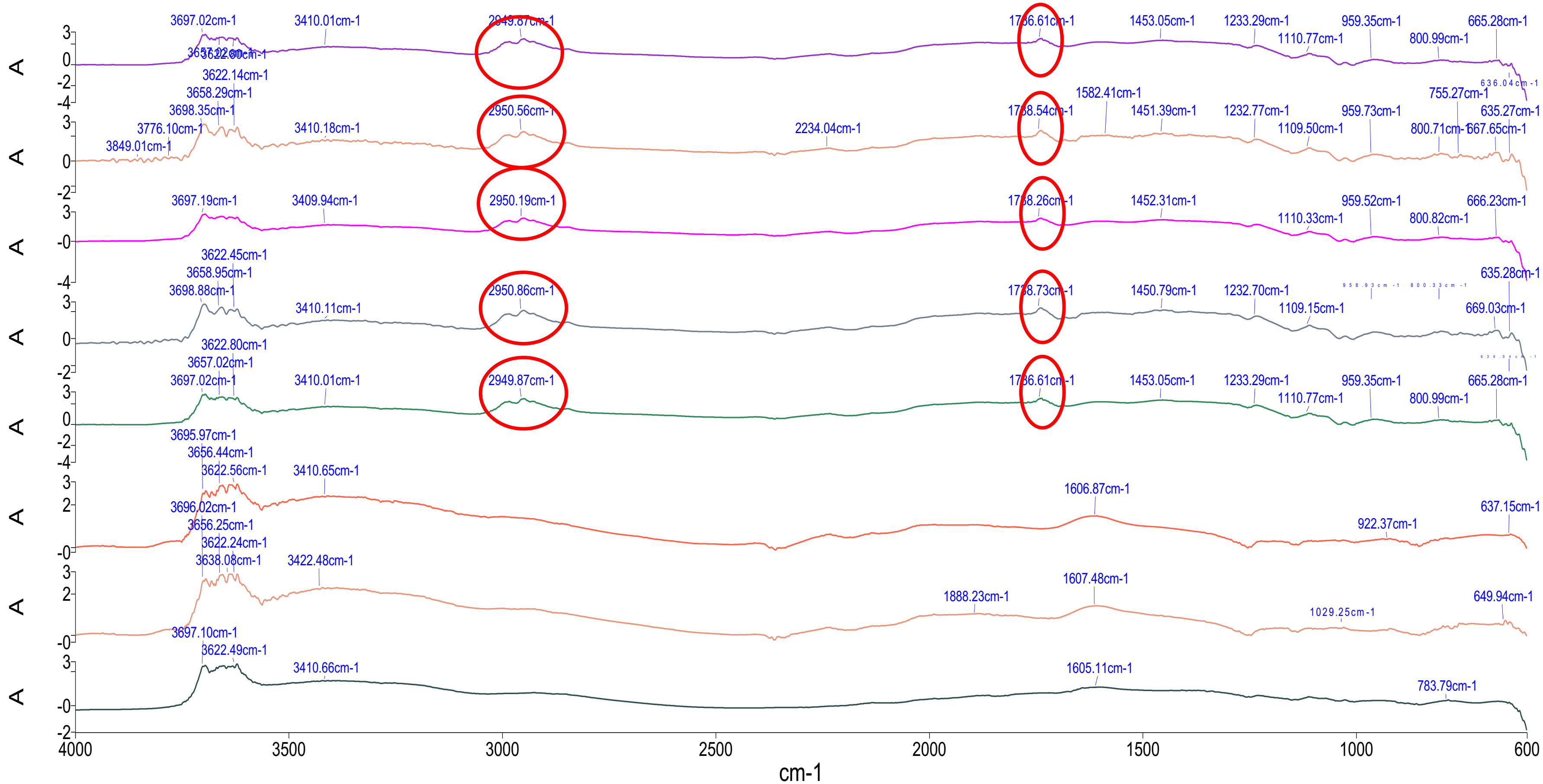


Figure 7.7 Spectra collected by FTIR Multiscope, cross-section analysis. 5% Paraloid B44 w/v in acetone. Two scans per location, in descending order: surface (purple and brown); break edge (pink and grey); 1mm depth (green and orange); 5mm depth (tan and grey). Diagnostic peaks indicating the presence of polymer circled in red.

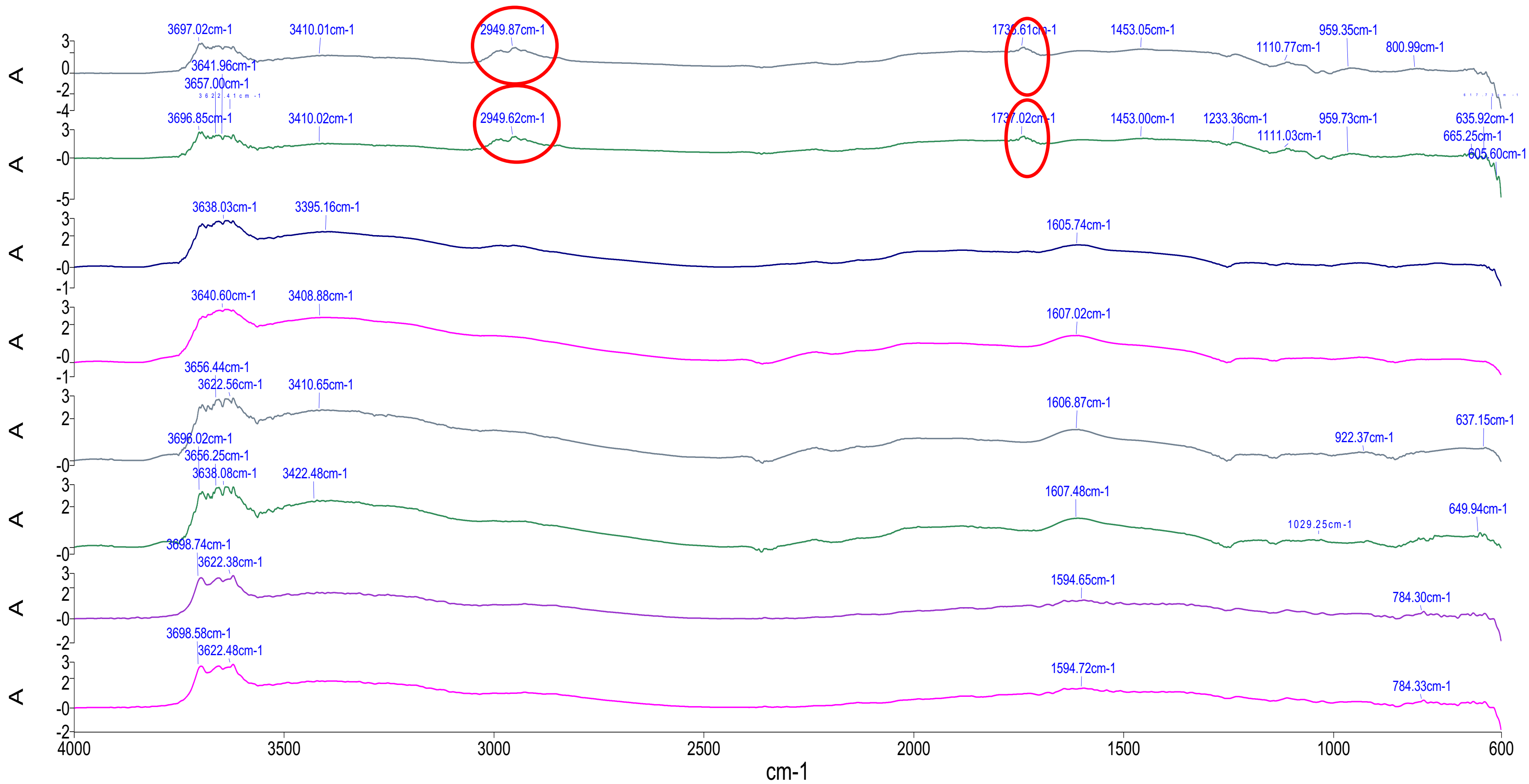


Figure 7.8 Spectra collected by FTIR Multiscope, cross-section analysis. 10% Paraloid B44 w/v in acetone. Two scans per location, in descending order: surface (grey and green); break edge (navy and pink); 1mm depth (grey and green); 5mm depth (purple and pink). Diagnostic peaks indicating the presence of polymer circled in red.

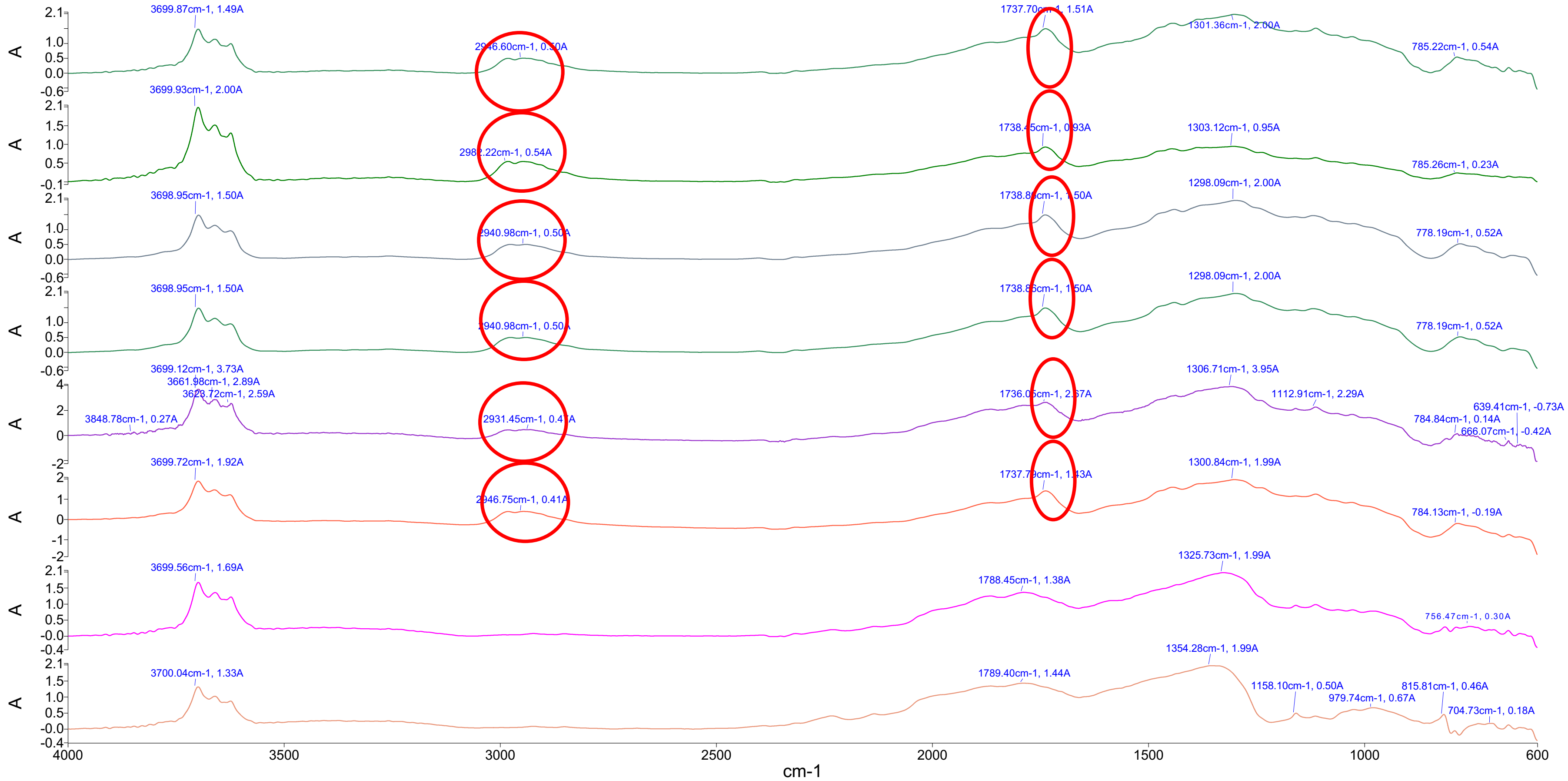


Figure 7.9 Spectra collected by FTIR Multiscope, cross-section analysis. 5% Paraloid B72 w/v in acetone. Two scans per location, in descending order: surface (teal and green); break edge (grey and green); 1mm depth (purple and orange); 5mm depth (pink and tan). Diagnostic peaks indicating the presence of polymer circled in red.

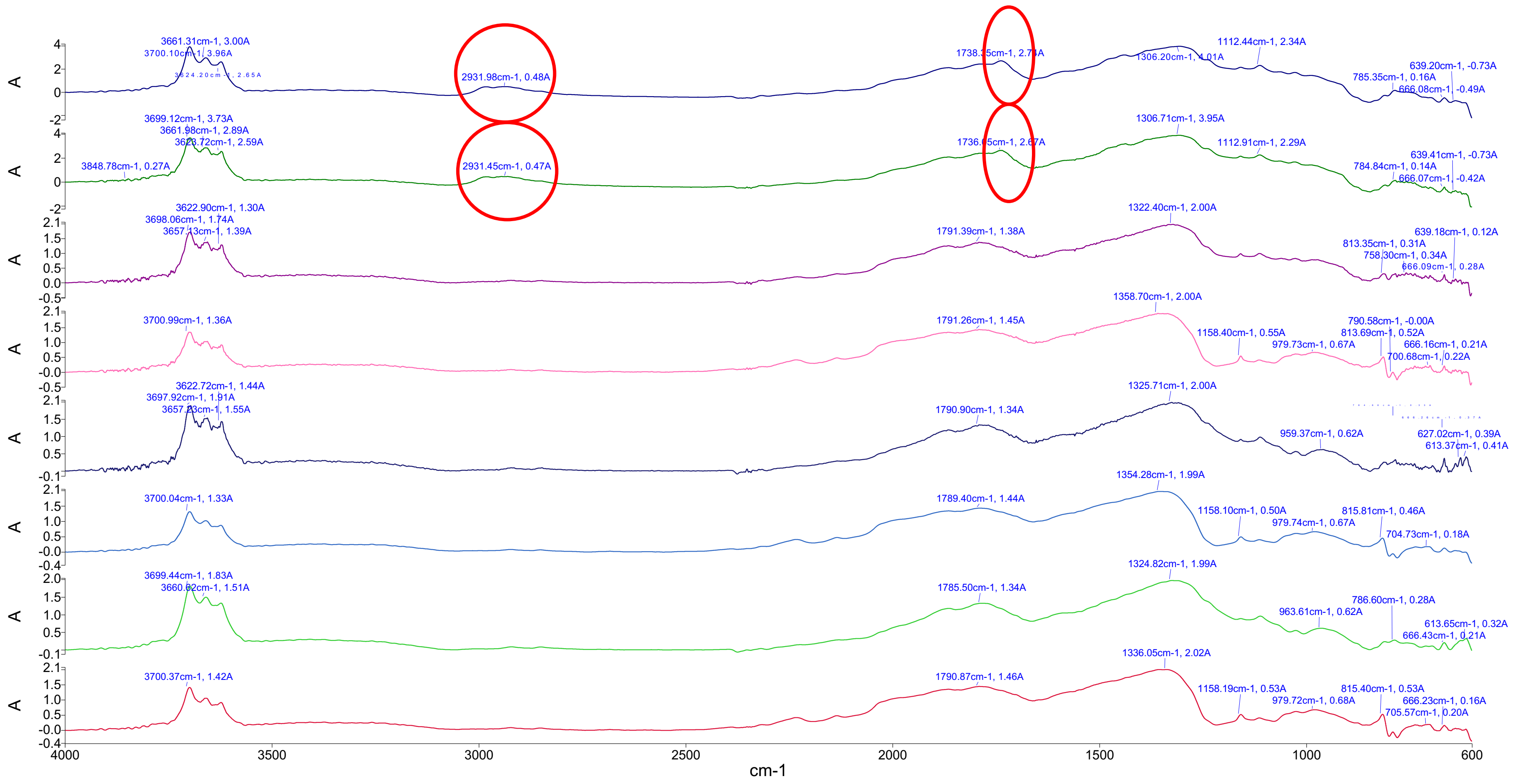


Figure 7.10 Spectra collected by FTIR Multiscope, cross-section analysis. 10% Paraloid B72 w/v in acetone. Two scans per location, in descending order: surface (navy and green); break edge (purple and pink); 1mm depth (navy and blue); 5mm depth (green and red). Diagnostic peaks indicating the presence of polymer circled in red.

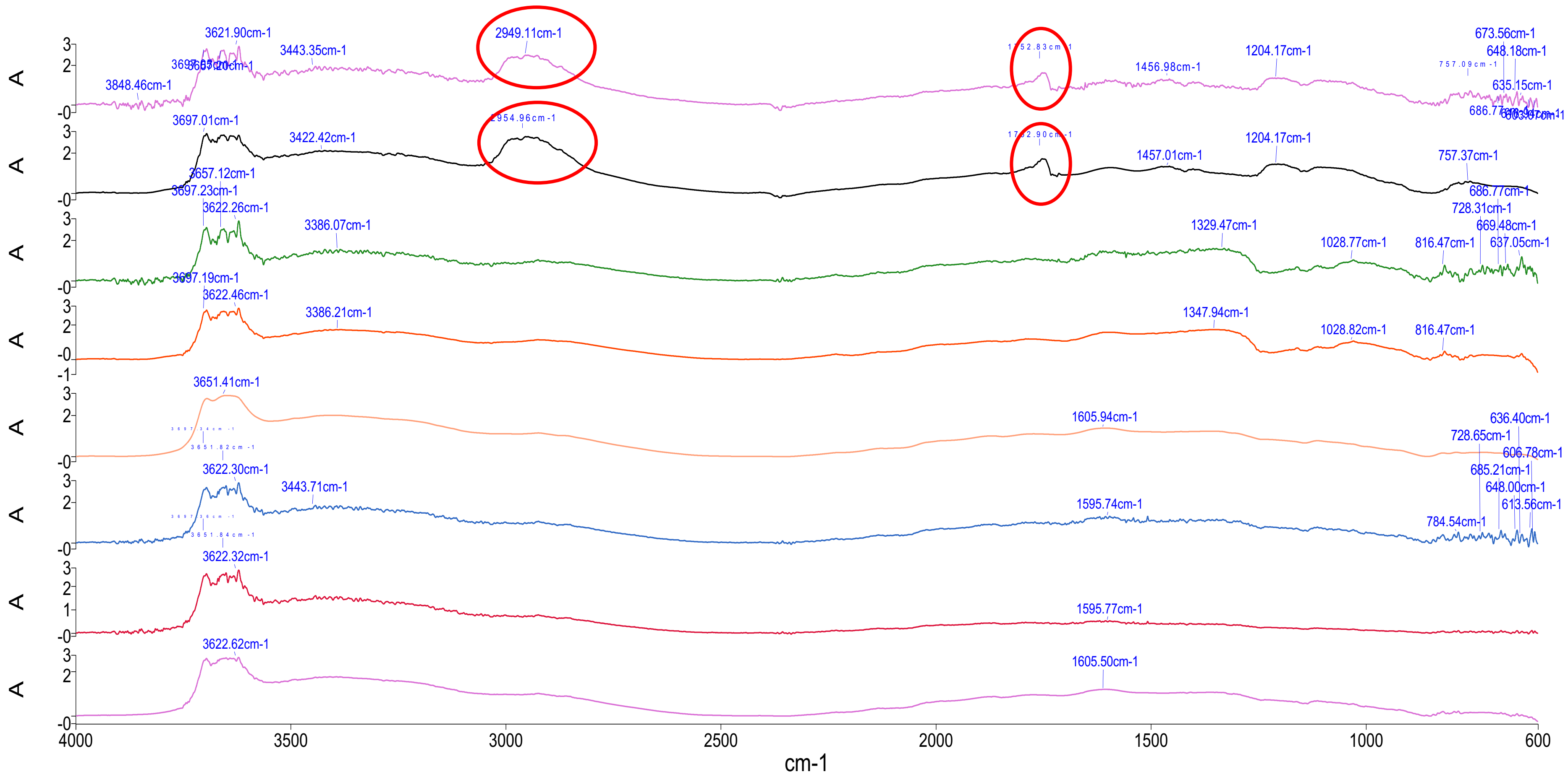


Figure 7.11 Spectra collected by FTIR Multiscope, cross-section analysis from analogue mudbrick consolidated with 5mls of 25% Primal B60A v/v in deionized water. In descending order: surface (pink and black), break-edge (green and orange), 1mm depth (peach and blue), 2mm depth (red and pink). Diagnostic peaks indicating the presence of polymer circled in red.

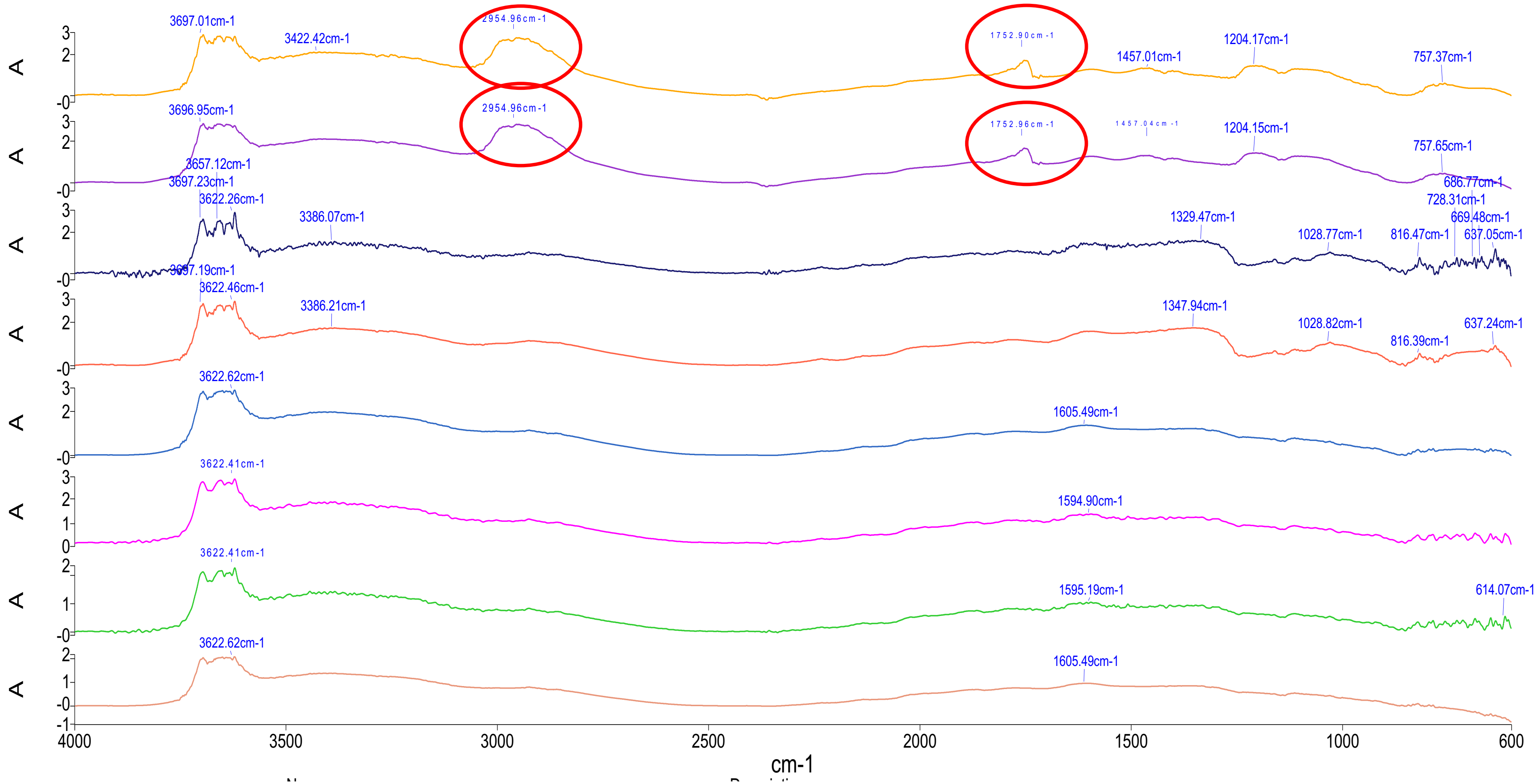


Figure 7.12 Spectra collected by FTIR Multiscope, cross-section analysis from analogue mudbrick consolidated with 5mls of 10% Primal B60A v/v in deionized water. In descending order: surface (yellow and purple), break-edge (navy blue and orange), 1mm depth (light blue and pink), 2mm depth (green and brown). Diagnostic peaks indicating the presence of polymer circled in red.

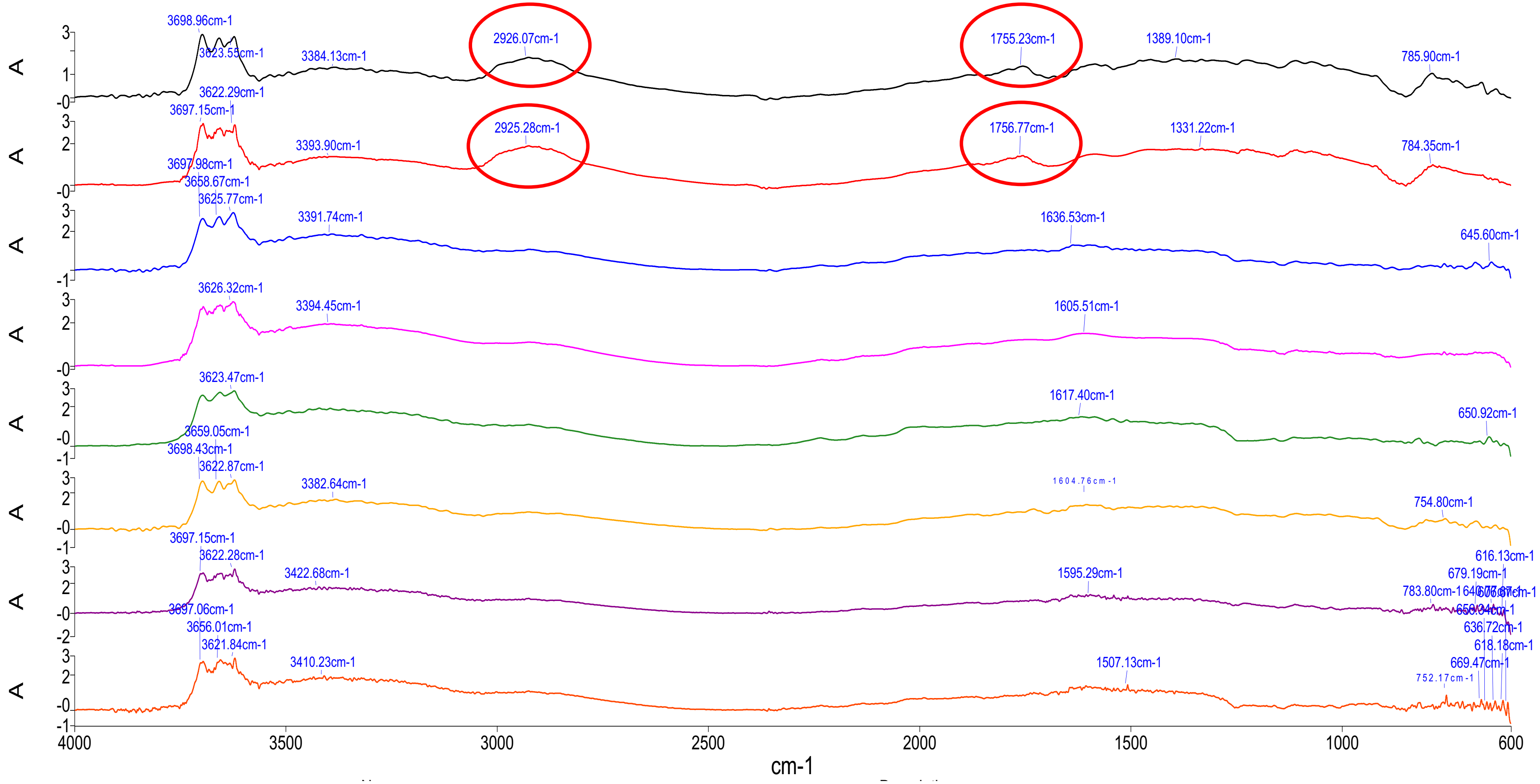


Figure 7.13 Spectra collected by FTIR Multiscope, cross-section analysis from analogue mudbrick consolidated with 5mls of 5% Primal B60A v/v in deionized water. In descending order: surface (black and red), break-edge (blue and pink), 1mm depth (green and yellow), 2mm depth (purple and orange). Diagnostic peaks indicating the presence of polymer circled in red

7.2.2 Çatalhöyük mudbrick: Çatalhöyük Archaeological samples and Çatalhöyük Analogues

Sixty-one archaeological samples from Çatalhöyük were analysed. Thirty-one of the samples had conservation records, implying they should have been consolidated. Twenty of the sixty-one samples had peaks for polymers present in the FTIR spectra, including four samples from the initial 1996 consolidation study conducted by Frank Matero. Figures 7.14 to 7.17 offer examples of the analysis of the archaeological samples. Figure 7.18 shows the results of consolidating the Çatalhöyük Analogue with 5% Primal B60A. Figure 7.19 shows surface spectra for all three samples types used in this study; Çatalhöyük sample, Çatalhöyük analogue, and laboratory analogue. Figures 7.20-7.22 demonstrate volumes for the diagnostic peaks from the three sample types. These peaks can act as a guide to the quantity of consolidant present provided they are scaled against standards.

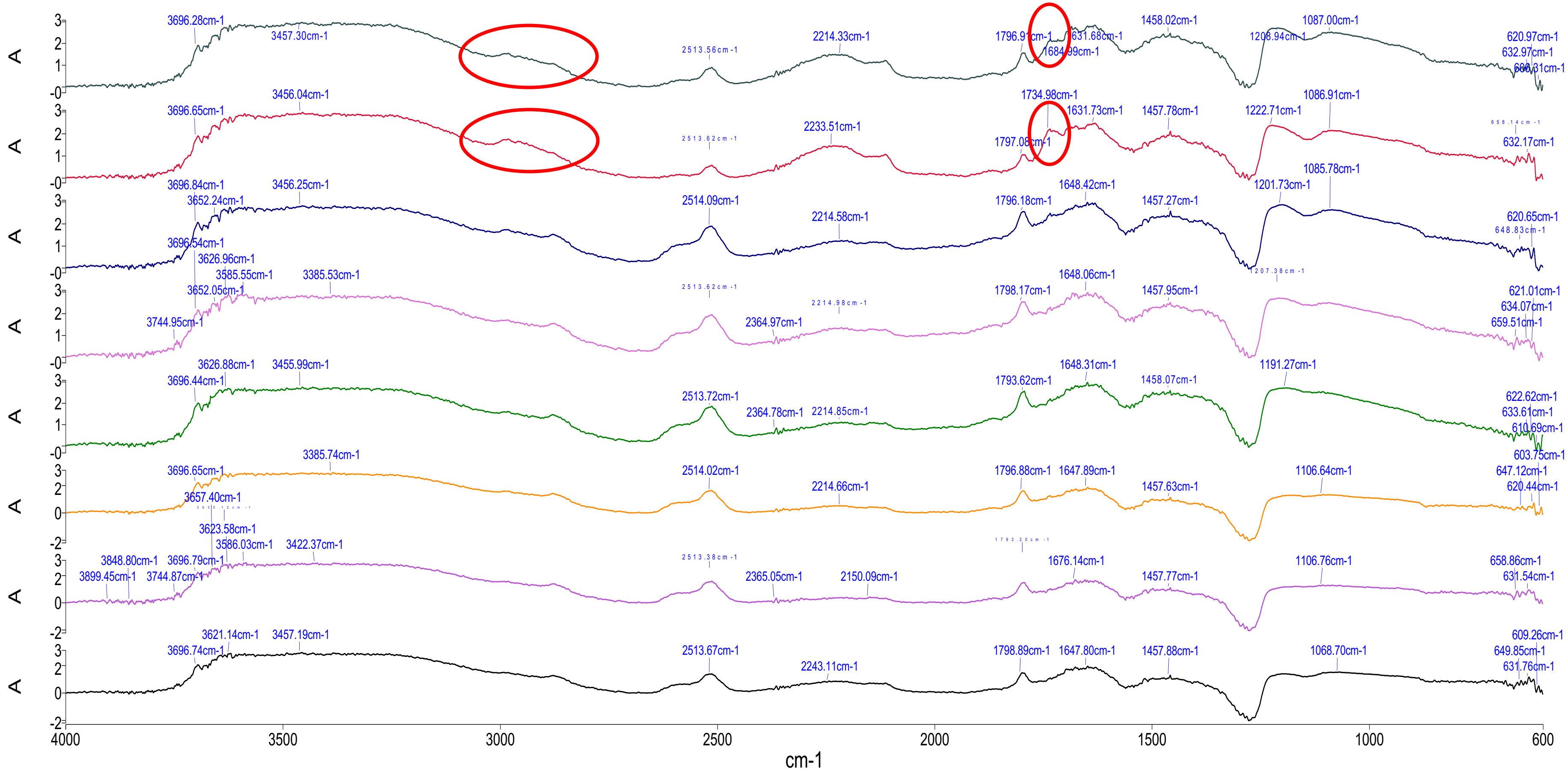


Figure 7.14 Çatalhöyük mudbrick (unit 17750, feature 1617, Building 82, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (grey and red); break-edge (blue and pink); 1mm depth (green and yellow); 5mm depth (purple and black). Diagnostic peaks indicating the presence of polymer Primal B60 circled on spectra.

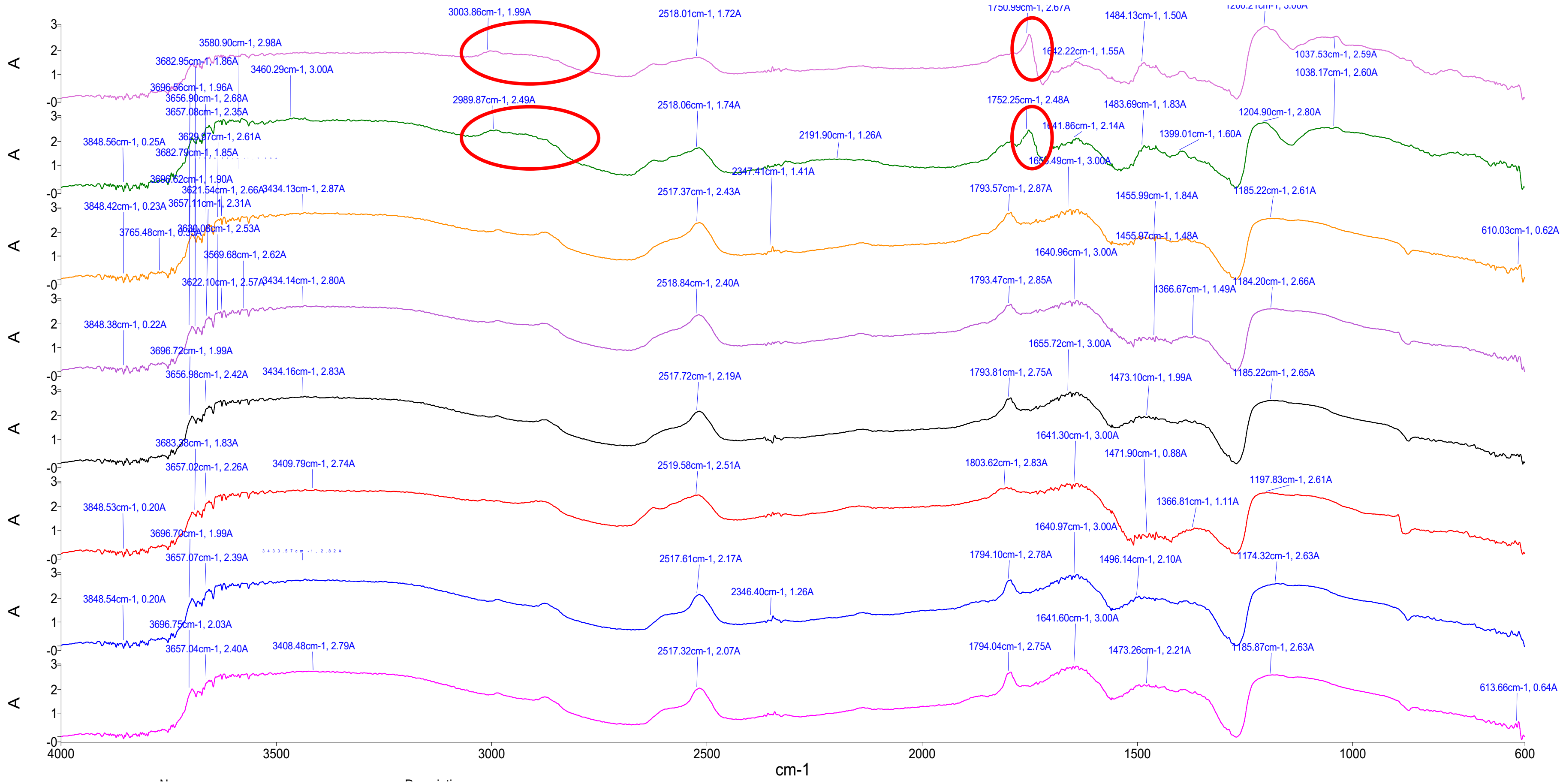


Figure 7.15 Çatalhöyük mudbrick (unit 16368, feature 1519, Building 55, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple); 1mm depth (black and red); 5mm depth (blue and pink). Diagnostic peaks indicating the presence of polymer Primal B60 circled on spectra.

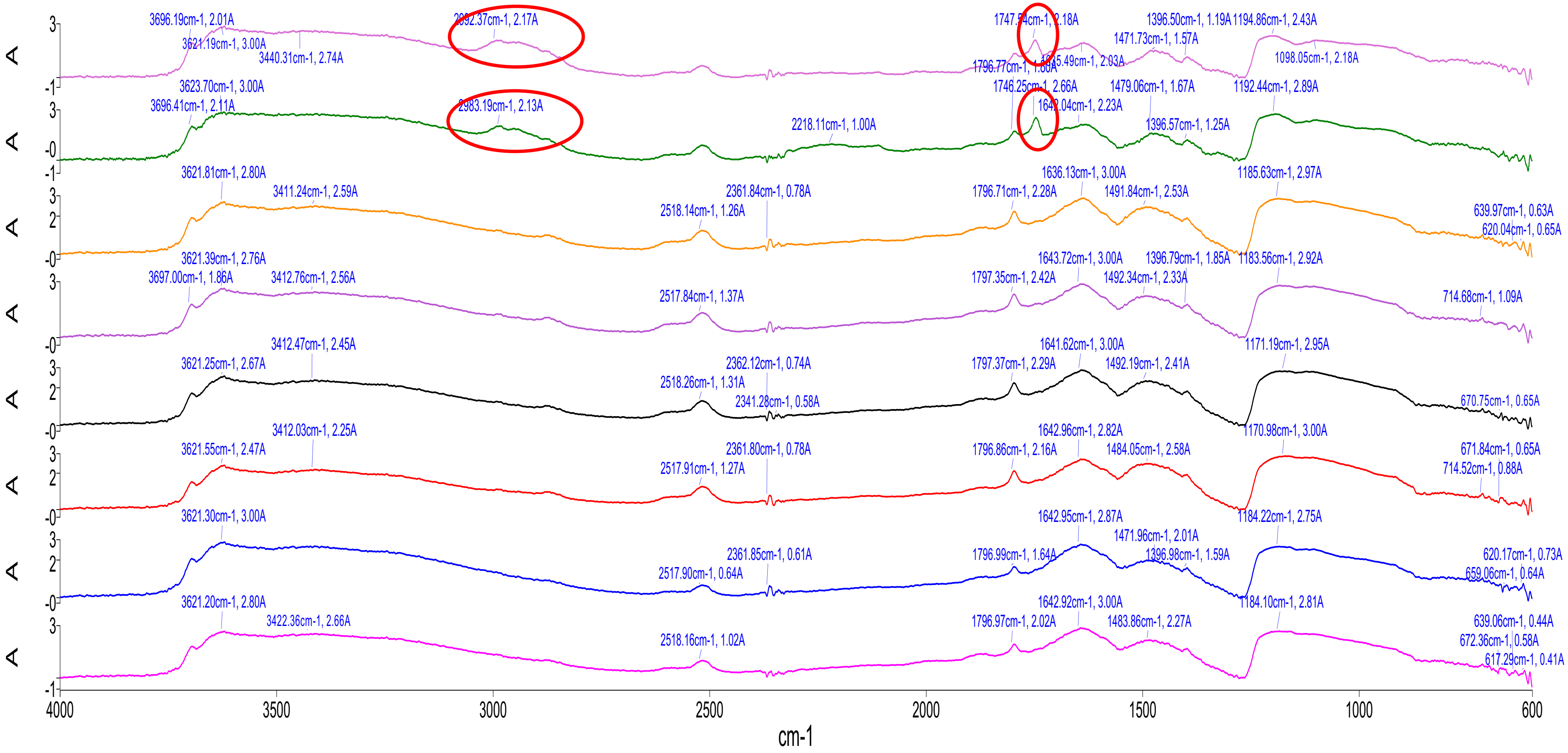


Figure 7.16 Çatalhöyük mudbrick (unit 4607, feature 484, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple); 1mm depth (black and red); 5mm depth (blue and pink). Diagnostic peaks indicating the presence of polymer Primal B60 circled on spectra.

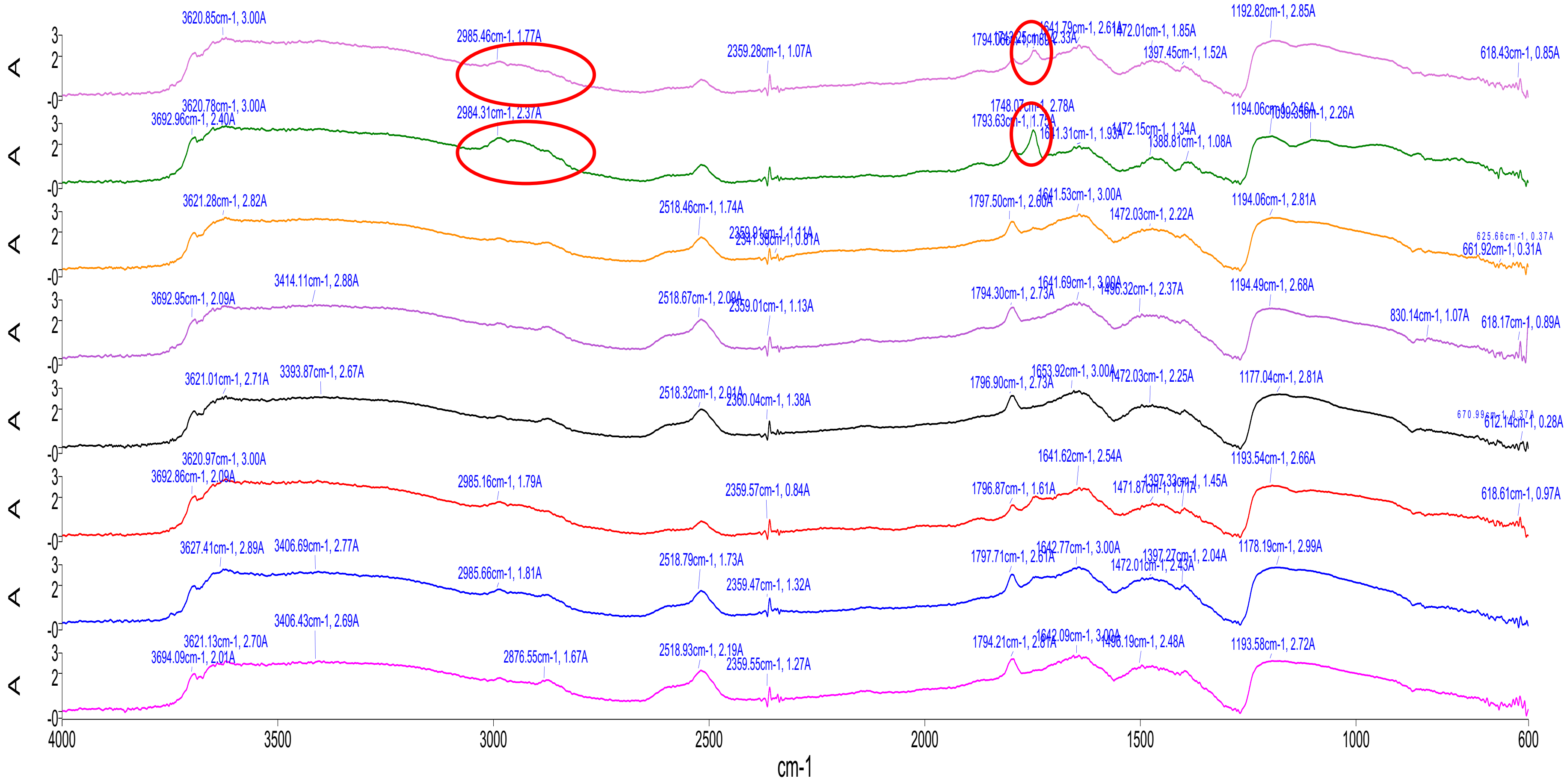


Figure 7.17 Çatalhöyük mudbrick (unit 22339, feature 3483, Building 89, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple); 1mm depth (black and red); 5mm depth (blue and pink). Diagnostic peaks indicating the presence of polymer Primal B60 circled on spectra.

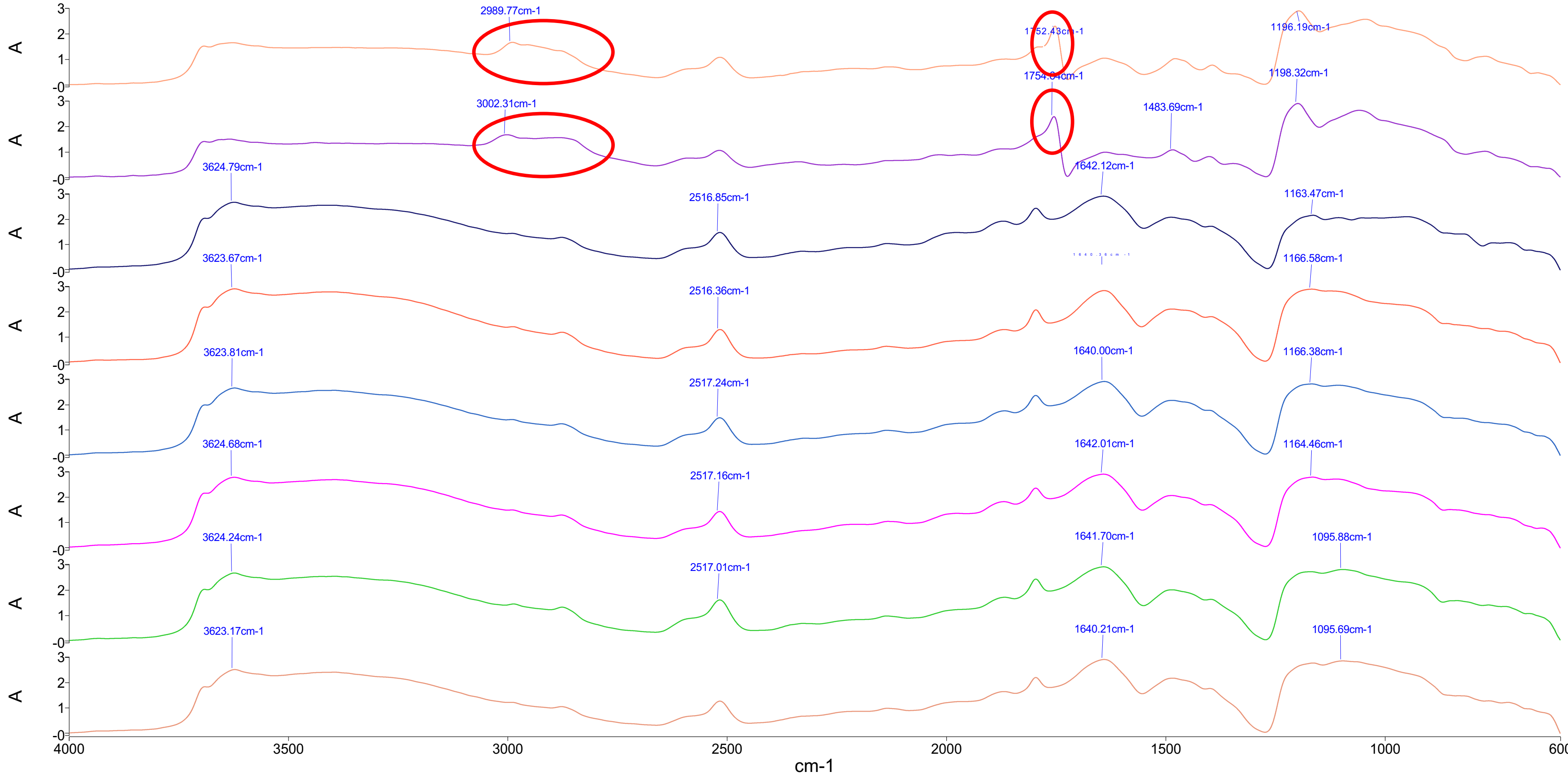


Figure 7.18 Çatalhöyük analogue mudbrick consolidated with 5% Primal B60A cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (peach and purple); break-edge (navy and orange); 1mm depth (blue and pink); 5mm depth (green and tan). Diagnostic peaks indicating the presence of polymer Primal B60 circled on spectra.

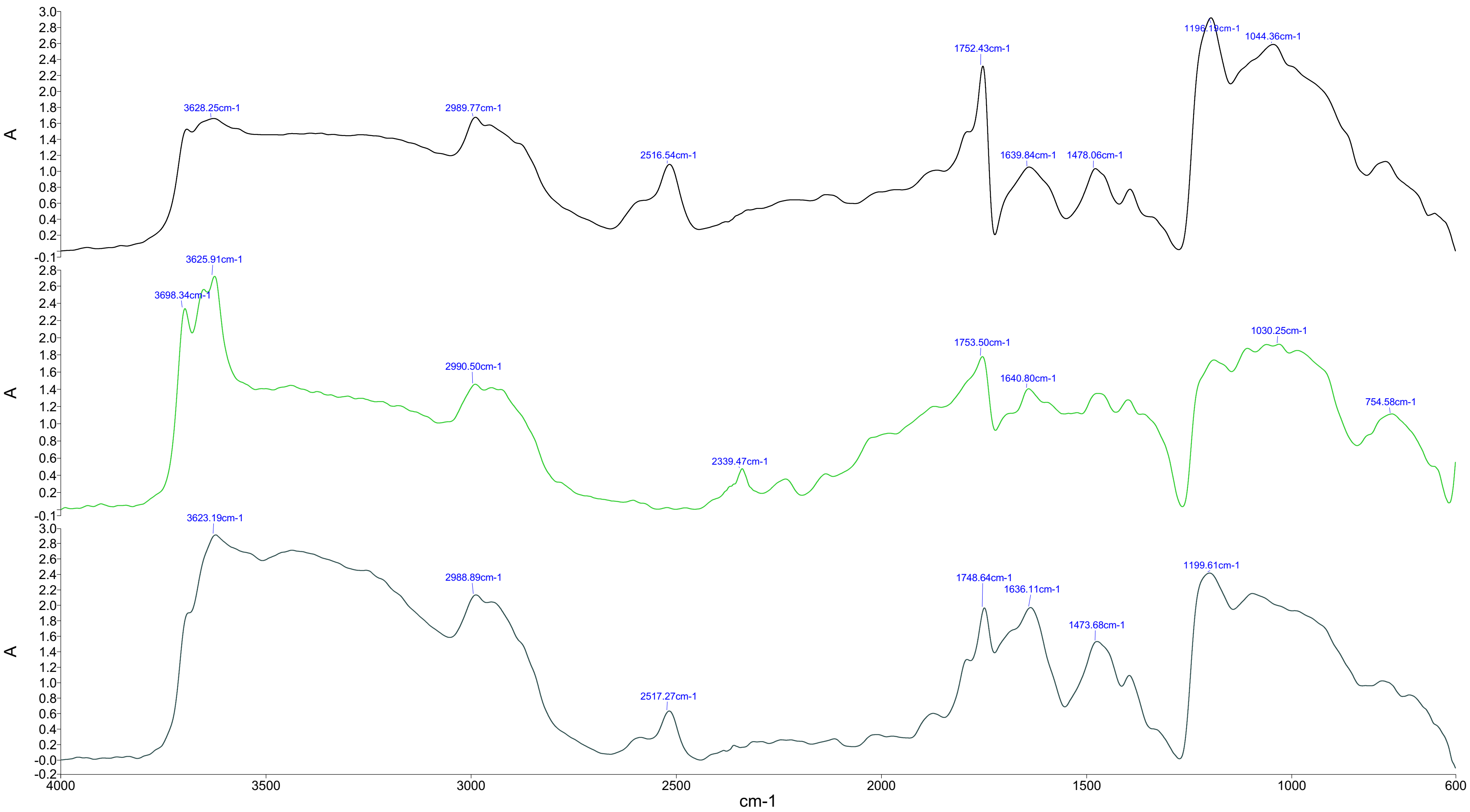


Figure 7.19 Spectra of sample surface scans in descending order: Çatalhöyük analogue (black), laboratory analogue (green), Çatalhöyük sample (grey). The analogue samples were consolidated in the laboratory with a 5% solution of Primal B60A v/v in deionized water. Archaeological samples consolidated with an unknown concentration of polymer.

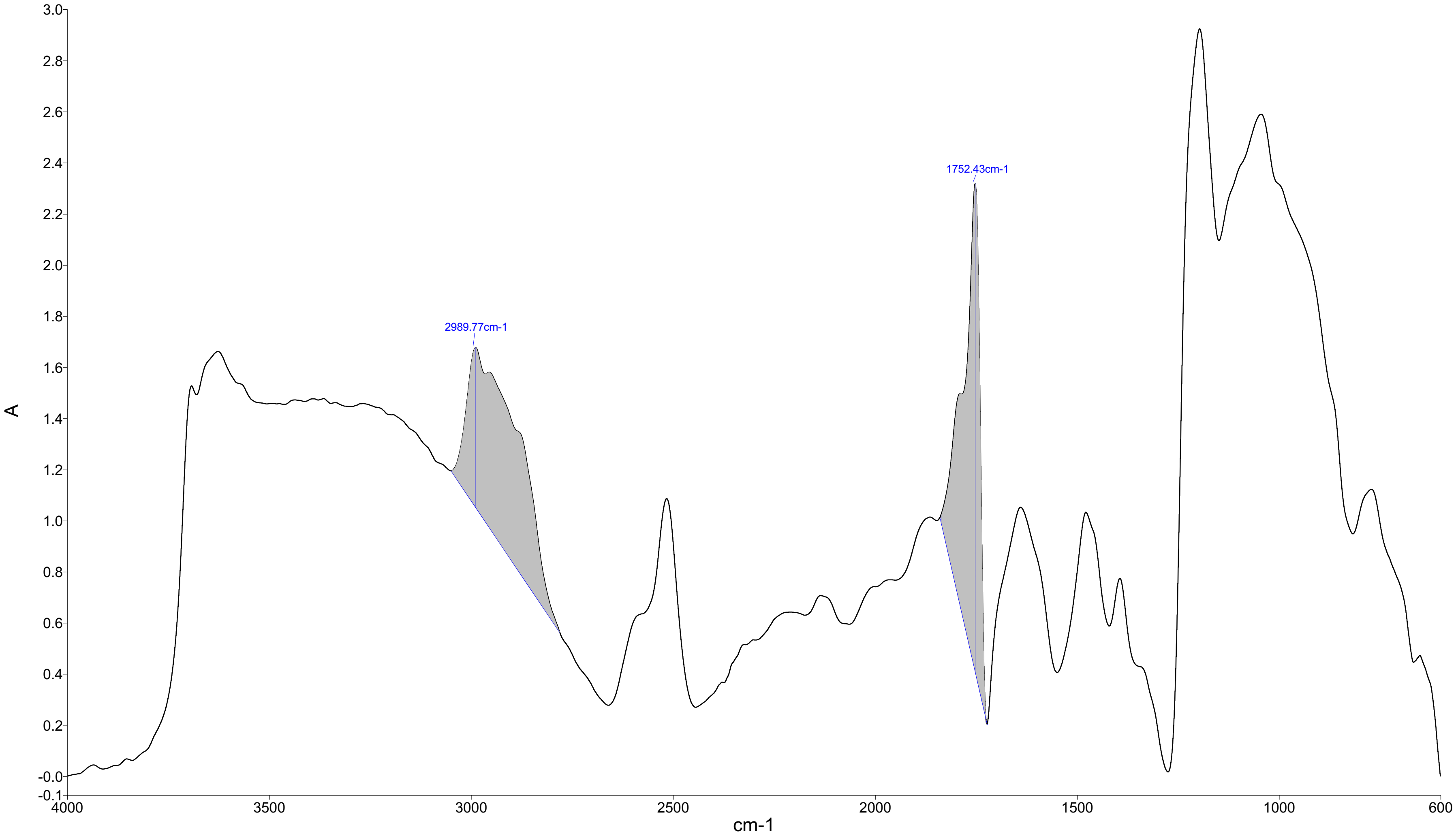


Figure 7.20 Peak volume from Çatalhöyük Analogue. Surface spectra collected by FTIR Multiscope. Peak 1, Alkanes peak area: 103.52, height: 0.6252; Peak 2, Carbonyl peak area:92.14, height: 1.9165.

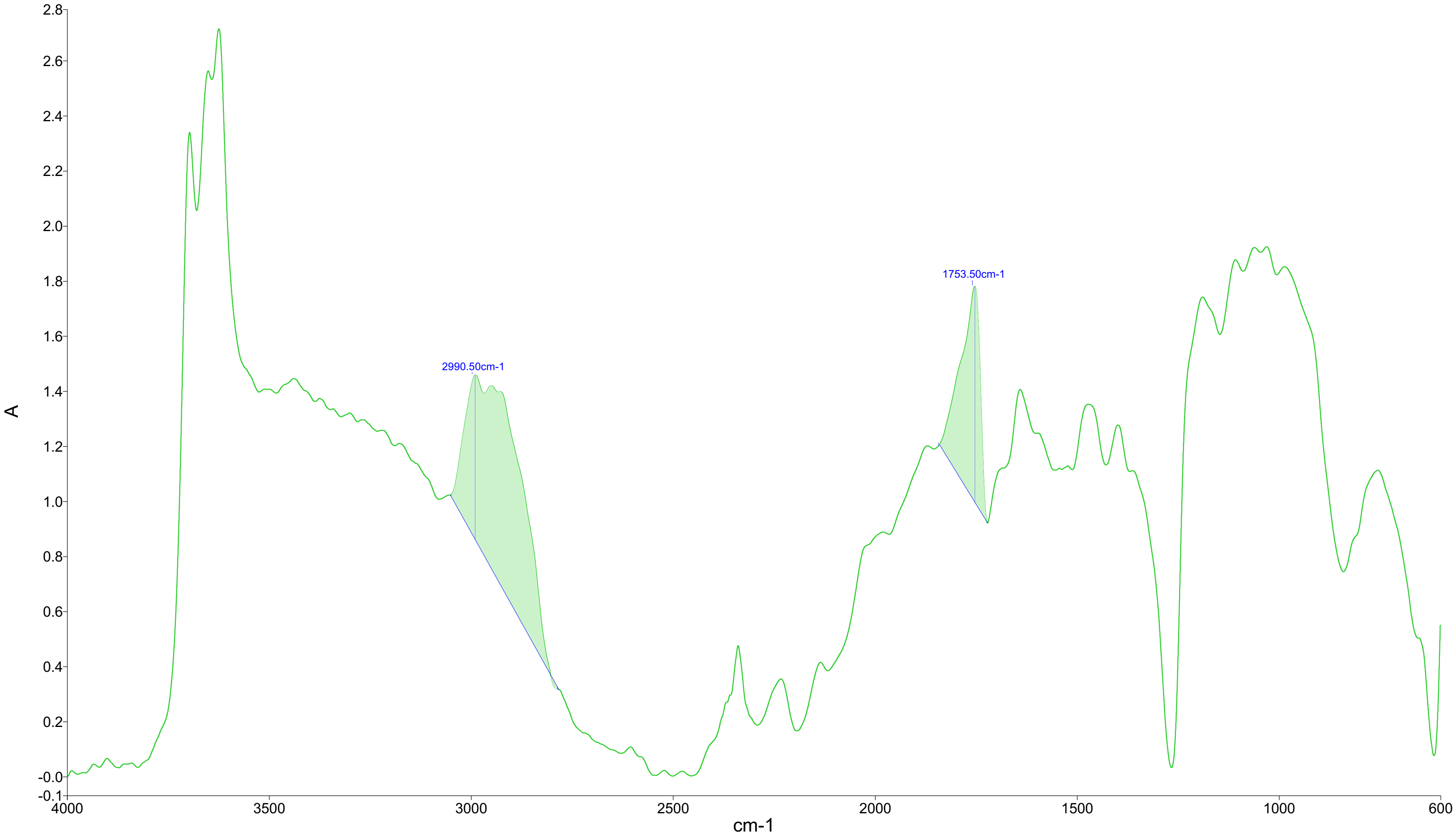


Figure 7.21 Peak volume from consolidated Laboratory Analogue. Surface spectra collected by FTIR Multiscope. Peak 1, Alkanes peak area:108.37, height:0.5971; Peak 2, Carbonyl peak area:43.27, height:0.7847.

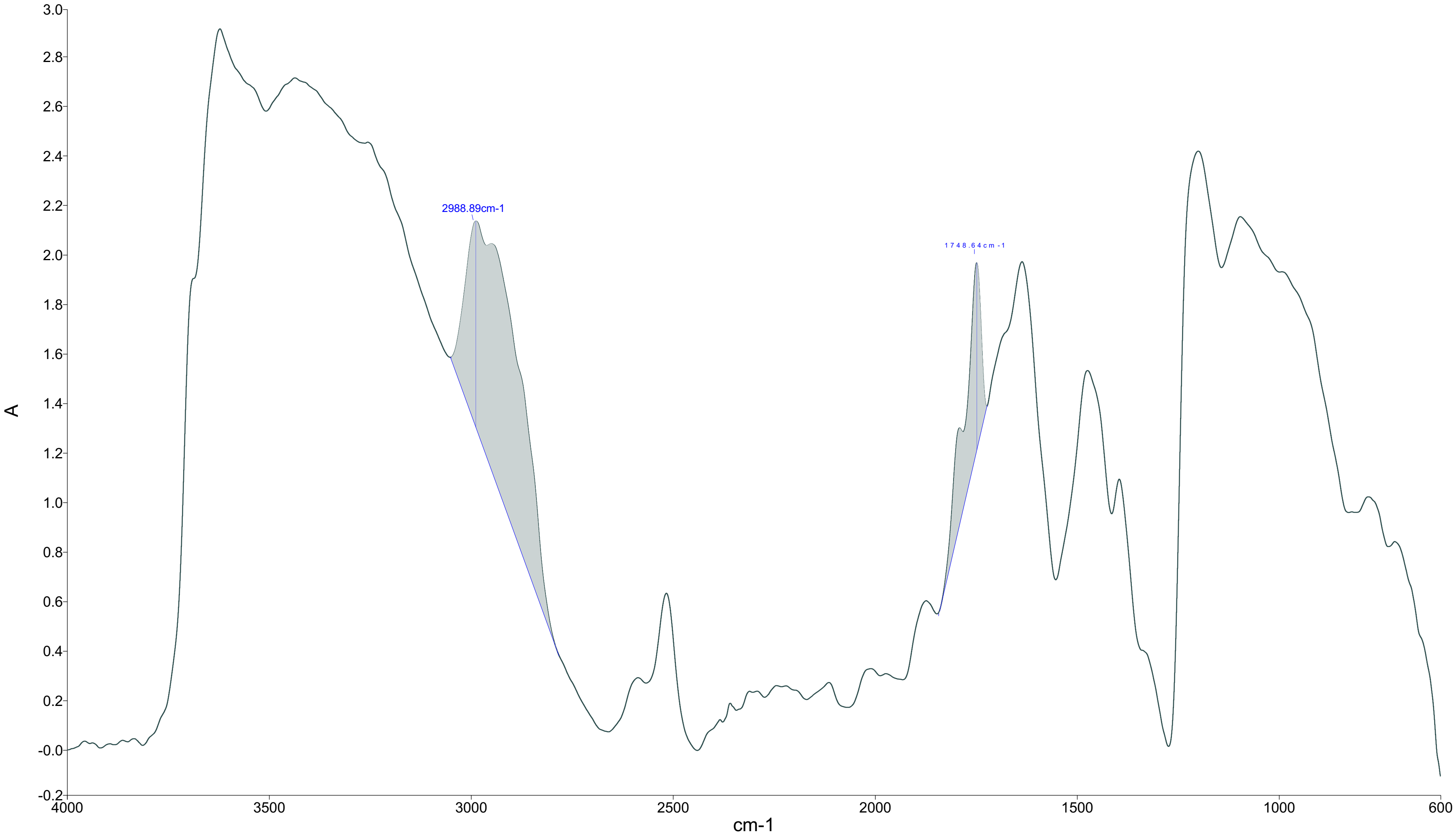


Figure 7.22 Peak volume from archaeological sample collected at Çatalhöyük (unit 4607, feature 484, Building 6, South Area surface spectra collected by FTIR Multiscope. Peak 1, Alkanes peak area:146.38, height:0.8326; Peak 2, Carbonyl peak area:36.26, height:0.7561.

7.3 UTM

Table 7.3 shows the average Fmax values at which the sample groups failed, which is defined as breakage. Figures 7.23 to 7.34 provide the data for individual analogue samples within a sample group.

Table 7.3 Average compression values at break point for each sample group.

Sample Group	Notation	Group Notation and dilution volume	$\bar{x}$ F_{max} N	$\bar{x}$ F_{max} mm
1	Mix5%	5% Mix (30mls)	14500	4.8
2	Mix15%	15% Mix (30mls)	5080	2.9
3	AP5%	5% Primal Mass (9mls)	1080	1.8
4	AP15%	15% Primal Mass (3mls)	1220	1.8
5	AS5%	5% AS (5mls)	1120	1.4
6	AS15%	15% AS (5mls)	991	1.6
7	50_25	50°C, 25% RH (4mls)	1450	1.7
8	40_90	40°C, 90% RH (4mls)	792	1.8
9	10_75	10°C, 75% RH (4mls)	951	1.6
10	10_25	10°C, 25% RH (4mls)	1030	1.6
11	UT	Untreated	1050	1.5
12	B44	5% Paraloid B44 (5mls)	1380	1.7

Sample Group 1

5% Mix

Heading : 5% Mix

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	15900	7.7	red
2	12900	5.1	light green
3	15900	4.7	blue
4	13800	4.8	orange
5	12600	4.3	pink
6	15400	4.2	turquoise
7	14800	4.3	yellow
8	14200	4.1	purple
9	15300	4.5	dark green
10	14300	4.1	brown

Series graph:

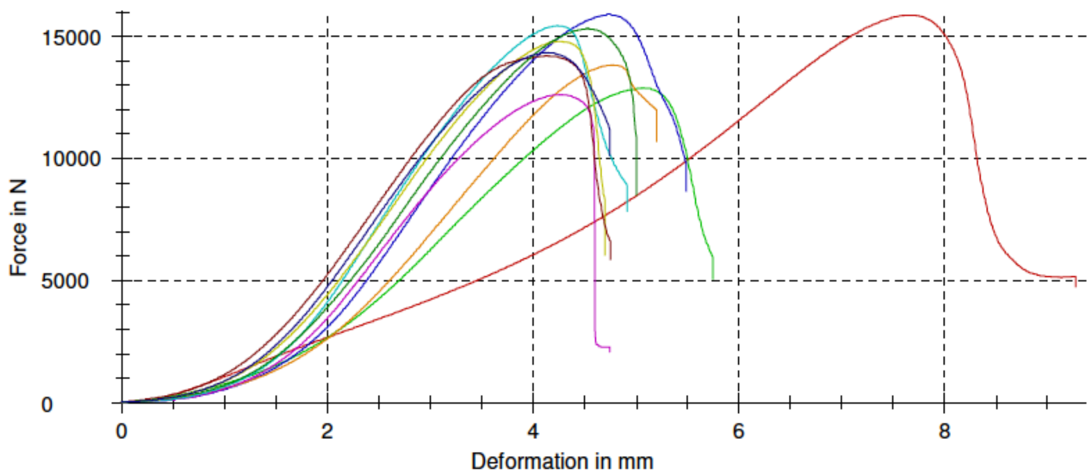


Figure 7.23 Sample Group 1. Representing ideally consolidated mudbricks. 30mls of 5% Primal B60A v/v in deionized water was fully incorporated into the substrate during manufacture of the mudbrick. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 2

15% Mix

Heading : 15% Mix

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	4110	2.4	red
2	4500	3.0	light green
3	4910	2.8	blue
4	6050	3.5	orange
5	7300	3.1	pink
6	4710	2.7	turquoise
7	5450	3.2	yellow
8	4890	2.9	borwn
9	4120	2.6	dark green
10	4770	3.2	purple

Series graph:

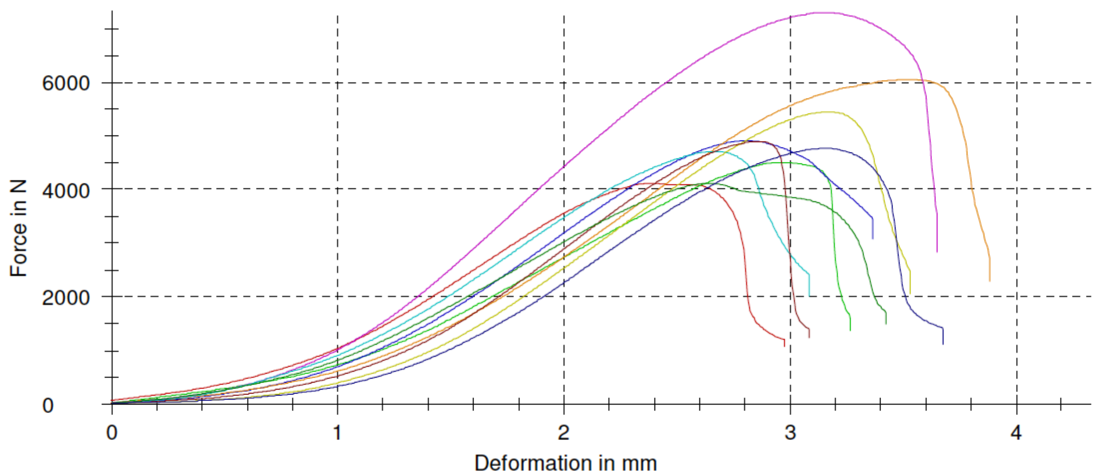


Figure 7.24 Sample Group 2. Representing ideally consolidated mudbricks. 30mls of 15% Primal B60A v/v in deionized water was fully incorporated into the substrate during manufacture of the mudbrick. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 3

AP 5%

Heading : AP 5%

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	908	1.9	red
2	709	2.1	light green
3	767	2.3	blue
4	1080	1.4	orange
5	1260	1.5	pinkl
6	1350	1.7	turquoise
7	1280	1.7	yellow
8	1310	2.0	brown
9	1240	1.9	dark green
10	886	1.6	purple

Series graph:

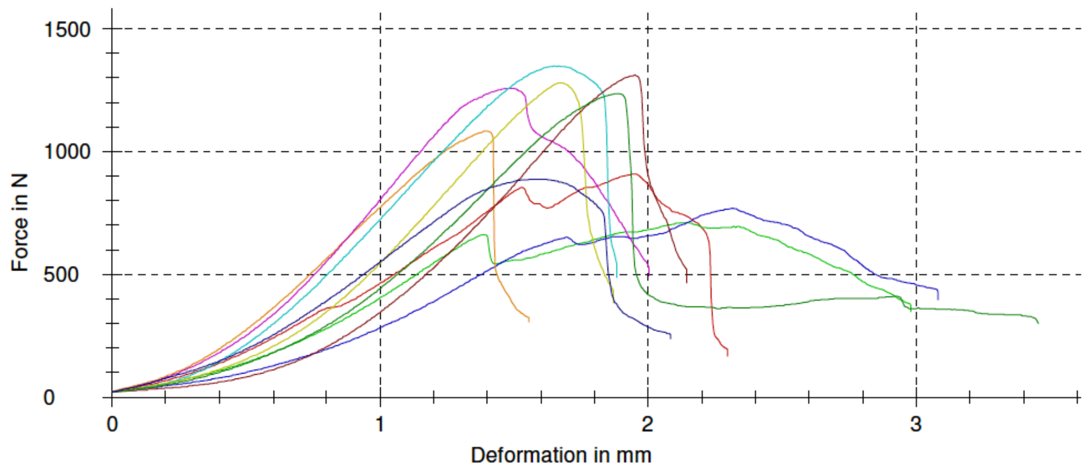


Figure 7.25 Sample Group 3. 9mls of 5% Primal B60A v/v in deionized water pipetted on the surface and dried in ambient laboratory conditions. This delivers the same mass of polymer as is applied to Sample Group 4. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 4

AP 15%

Heading : AP 15%

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1580	1.7	red
2	1350	1.8	light green
3	671	1.7	blue
4	1230	1.4	orange
5	1370	2.0	pink
6	1180	1.7	turquoise
7	611	1.3	yellow
8	1420	1.8	brown
9	1430	2.4	dark green
10	1350	2.0	purple

Series graph:

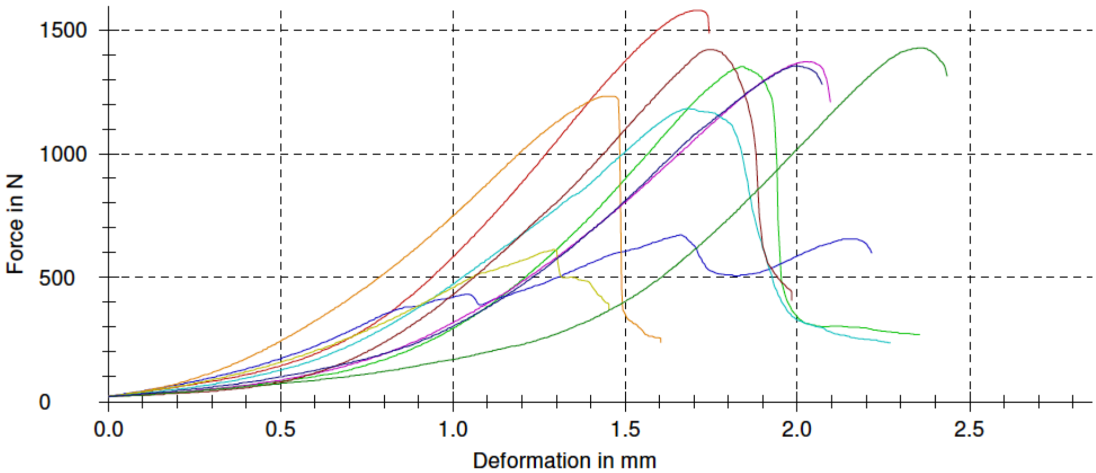


Figure 7.26 Sample Group 4. 3mls of 15% Primal B60A v/v in deionized water pipetted on the surface and dried in ambient laboratory conditions. This delivers the same mass of polymer as is applied to Sample Group 3. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 5

AS 5%

Heading : AS 5%

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1190	1.1	red
2	959	1.4	light green
3	847	1.3	turquoise
4	848	1.6	orange
5	991	1.4	pink
6	816	1.3	blue
7	935	1.3	yellow
8	1670	1.8	brown
9	1280	1.5	dark green
10	1670	1.6	purple

Series graph:

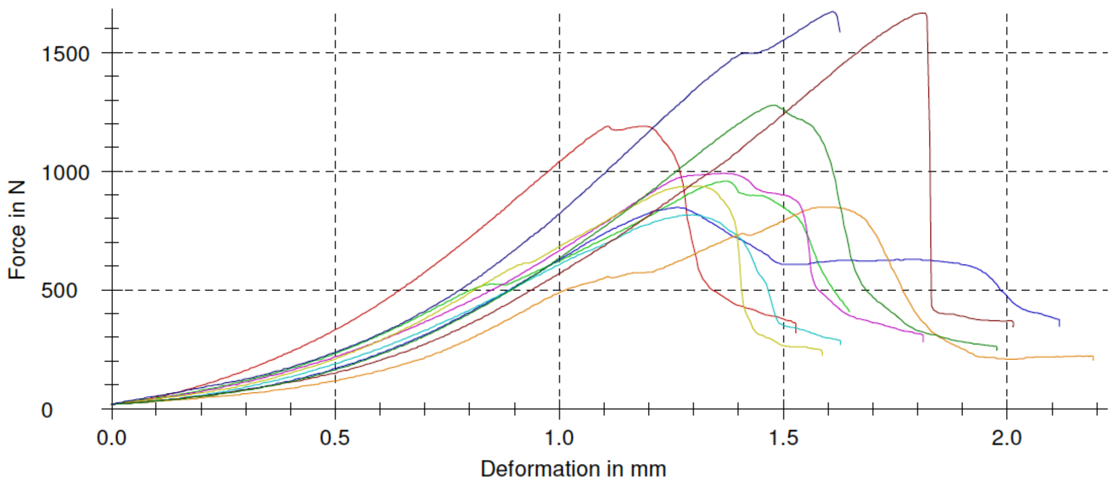


Figure 7.27 Sample Group 5. 5mls of 5% Primal B60A v/v in deionized water pipetted on the surface and dried in ambient laboratory conditions. This delivers the same volume of dilution as is applied to Sample Group 6. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 6

AS 15%

Heading : AS 15%

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1080	1.4	brown
2	959	1.6	light green
3	740	1.3	blue
4	812	1.7	orange
5	899	2.2	pink
6	979	1.7	turquoise
7	1250	1.6	yellow
8	1140	1.4	purple
9	860	2.1	dark green
10	1190	1.3	red

Series graph:

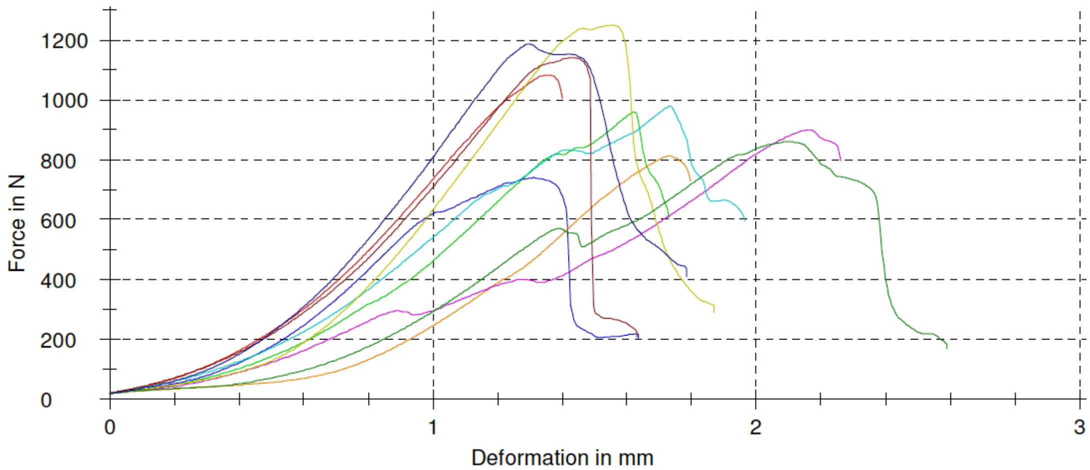


Figure 7.28 Sample Group 5. 5mls of 15% Primal B60A v/v in deionized water pipetted on the surface and dried in ambient laboratory conditions. This delivers the same volume of dilution as is applied to Sample Group 5. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 7

50 25

Heading : 50 25

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1450	1.4	red
2	1900	2.0	light green
3	1500	1.6	blue
4	1470	1.6	orange
5	1210	1.8	pink
6	1030	1.2	turquoise
7	1190	1.8	yellow
8	1400	1.7	brown
9	1660	2.3	dark green
10	1700	1.6	purple

Series graph:

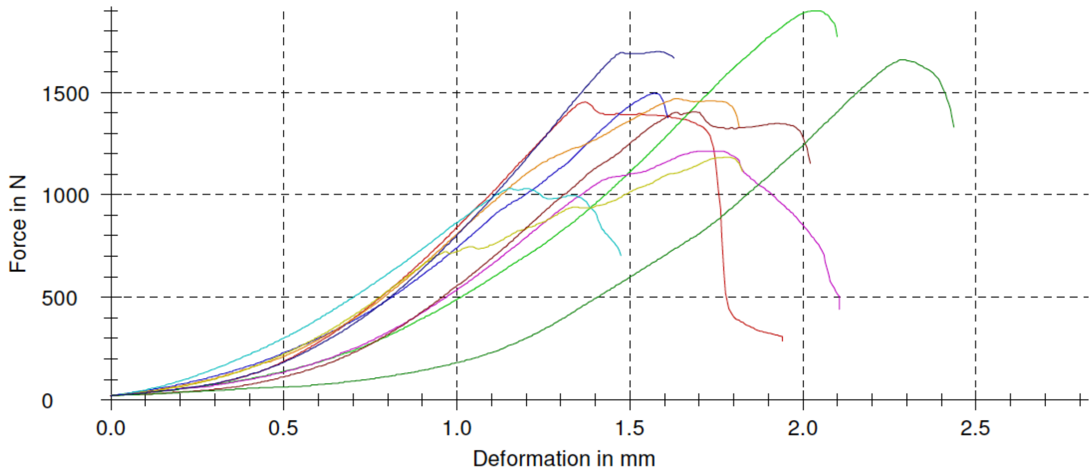


Figure 7.29 Sample Group 7. Environmental curing group. Arid climate prepared at 50°C and 25% RH. 5mls of 5% Primal B60A v/v in deionized water pipetted on the surface and dried at 50°C and 25% RH. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 8

40 90

Heading : 40 90
Customer :

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	707	1.2	red
2	754	1.8	light green
3	786	2.5	blue
4	1210	2.1	orange
5	708	1.8	pink
6	751	1.8	turquoise
7	796	1.8	yellow
8	769	1.8	brown
9	737	1.6	purple
10	706	1.6	dark green

Series graph:

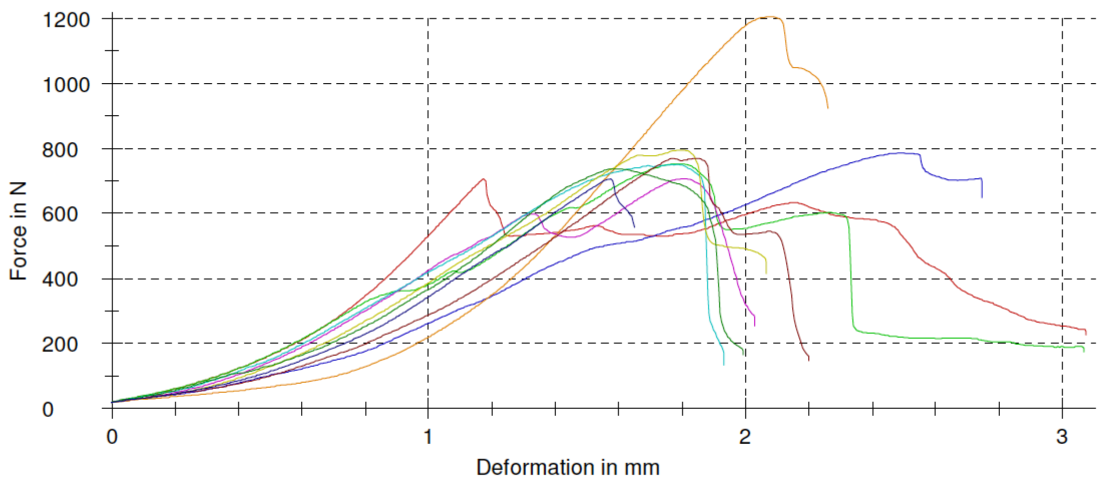


Figure 7.30 Sample Group 8. Environmental curing group. Tropical climate prepared at 40°C and 90%RH. 5mls of 5% Primal B60A v/v in deionized water pipetted on the surface and dried at 40°C and 90% RH. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 9

10 75

Heading : 10 75
Customer :

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1230	1.9	red
2	898	1.3	light green
3	826	1.5	purple
4	763	1.5	orange
5	924	1.7	pink
6	814	1.8	turquoise
7	1060	1.6	yellow
8	715	1.8	brown
9	1130	1.7	dark green
10	1150	1.6	blue

Series graph:

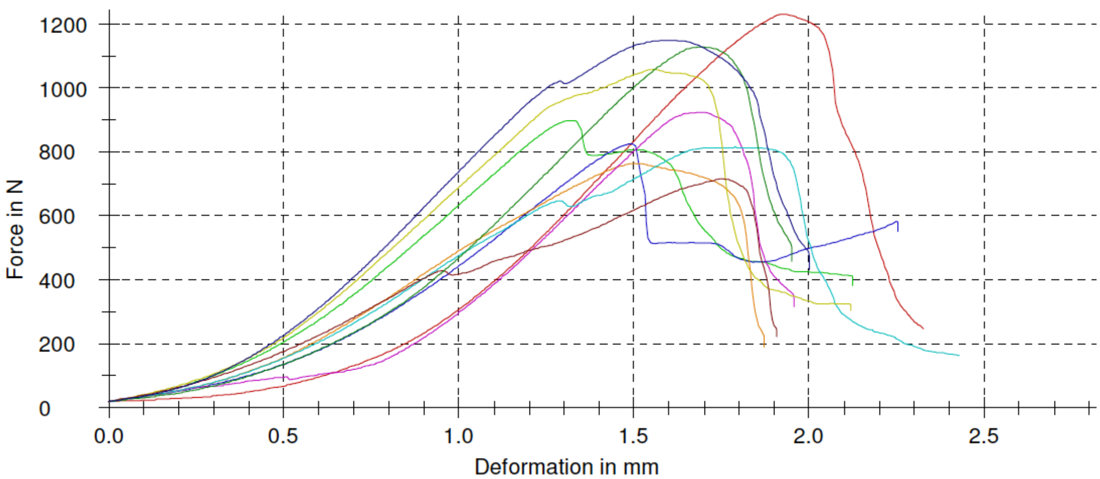


Figure 7.31 Sample Group 9. Environmental curing group. Mild climate prepared at 10°C and 75%RH. 5mls of 5% Primal B60A v/v in deionized water pipetted on the surface and dried at 10°C and 75% RH. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 10

10 25

Heading : 10 25
Customer :

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	913	1.3	red
2	1020	2.2	light green
3	1520	1.5	blue
4	1410	1.9	orange
5	1040	2.1	pink
6	926	1.5	turquoise
7	796	1.2	yellow
8	1070	1.5	brown
9	966	1.7	dark green
10	619	1.6	purple

Series graph:

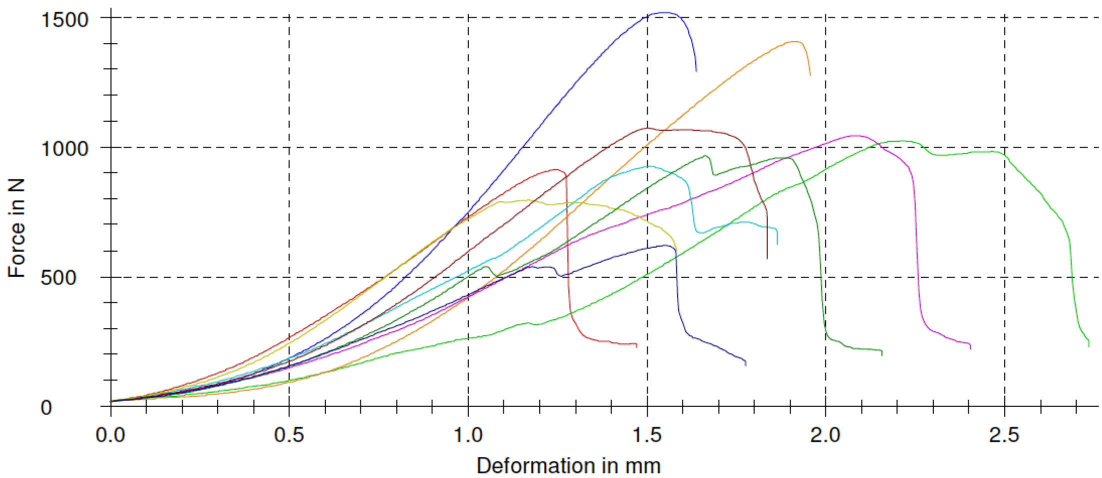


Figure 7.32 Sample Group 10. Environmental curing group. Continental climate prepared at 10°C and 25%RH. 5mls of 5% Primal B60A v/v in deionized water pipetted on the surface and dried at 10°C and 25% RH. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 11

Untreated

Heading : Untreated
Customer :

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1210	1.4	red
2	935	1.3	light green
3	776	1.9	blue
4	1040	1.9	orange
5	1260	1.3	pink
6	910	1.5	turquoise
7	980	1.4	yellow
8	1160	1.5	brown
9	1220	1.7	dark green
10	1060	1.6	purple

Series graph:

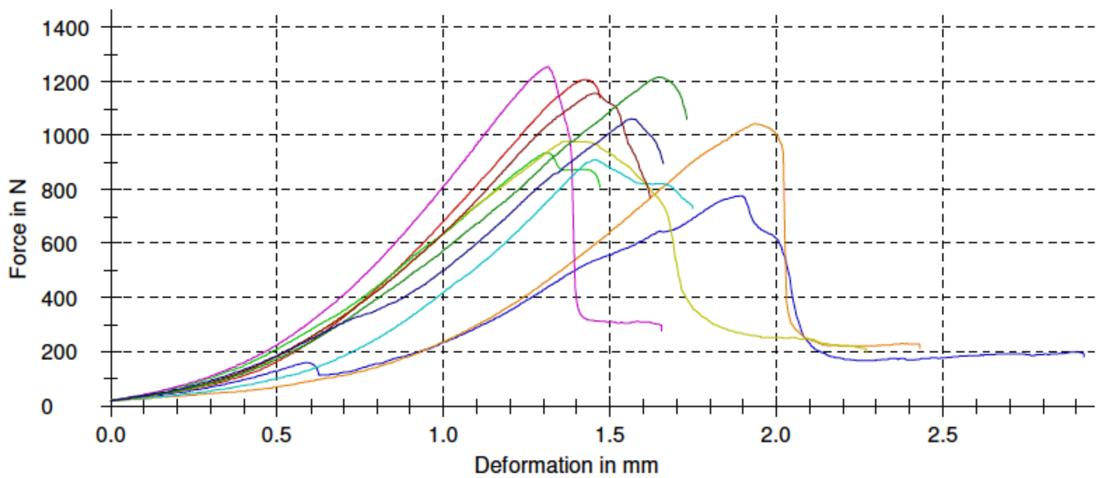


Figure 7.33 Sample Group 11. Untreated samples. Prepared in ambient laboratory conditions, no polymers applied. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

Sample Group 12

B44 5%

Heading : B44 5%

Pre-load : 20 N
Test speed : 3 mm/min

Test results:

Sample No.	Fmax N	dL at Fmax mm	Identifier
1	1360	1.6	pink
2	1670	1.7	light green
3	1650	1.9	blue
4	1630	1.8	orange
5	1390	1.8	red
6	1240	1.2	turquoise
7	1520	1.5	yellow
8	840	1.6	brown
9	1250	1.8	dark green
10	1260	2.2	purple

Series graph:

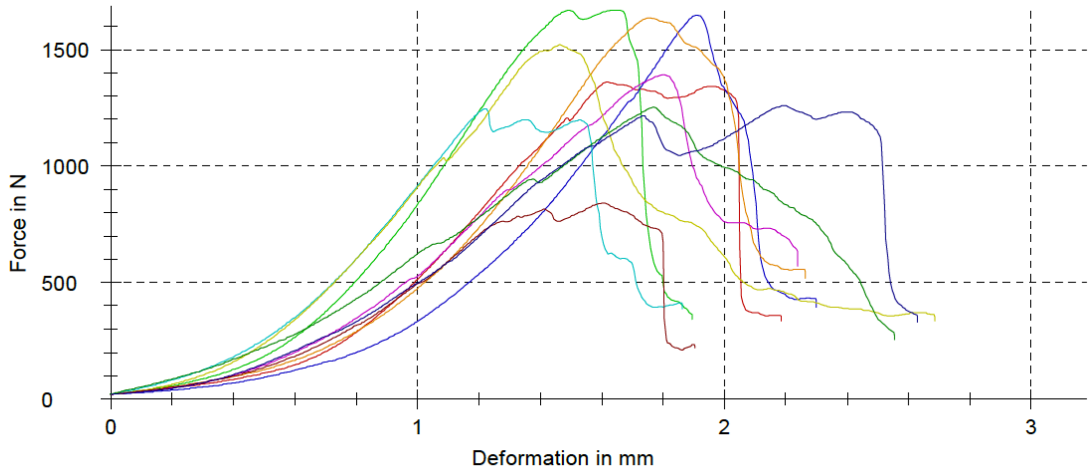


Figure 7.34 Sample Group 12. Analogue mudbricks consolidated with 5mls of 5% Paraloid B44 w/v in acetone in ambient laboratory conditions. Each line maps the deformation an individual mudbrick created for this experiment, with colour identifiers listed in the test results.

7.3.1 UTM Summary

Having identified the limited penetration of polymer dispersions and solutions into mudbrick through FTIR analysis, the question of whether the physical integrity of the analogue changes as a result of the surface consolidation remined. The UTM tests utilised Laboratory Analogues consolidated with polymers dissolved in organic solvents or dispersions were tested and some of these were dried in conditions that replicated specific climates (Table 6.6). For comparative purposes, strength imparted by idealised consolidation was investigated using analogues formed by including consolidant in the mixing process. Additionally, untreated samples were also tested. Further discussion is offered in section 8.5.

8 Discussion

8.1 Overview

The experimental design explored the reality of consolidation of mudbrick. If something lacks physical integrity and is crumbing, conservators normally adopt consolidation processes, selecting the consolidant from a very small range of organic polymer systems. Operational controls are almost invariably basic, involving manipulation of consolidant concentration and volume, which is applied by spraying, brushing and injection. Determining end point is empirical, typically relating to observations that the matrix will not accept any more liquid consolidant. In the face of there being inevitable total loss if no intervention takes place, there is a belief that consolidation is 'the only thing to do' and that it will 'improve the strength of the substrate'. This decision seems logical but what does consolidation achieve? This experimental study addressed this question by replicating conservation procedures in a controlled and measurable way to produce semi-quantitative data that contributes to a better understanding of the empirical concept of what consolidation procedures achieve.

First, the suitability of the FTIR experimental methodology for detecting low levels of polymer within earth matrices was confirmed. This was then used to explore the commonly held belief that polymer solutions or dispersions applied to mudbrick permeate its fabric and strengthened it. Standardisation and reproducibility were at the core of the study, which used mudbrick analogues to study consolidation procedures. The final questions centred on what strength gains can be attributed to empirical field consolidation procedures and what would an 'ideal' consolidation produce in terms of increased strength. In the process of doing this, other factors such as the influence of climate, consolidant form (solutions or dispersion) and concentration received some preliminary investigation.

8.2 Limits of detection of polymer within earth mudbrick analogues using FTIR

Detection of the Primal B60A polymer within Lab Analogue earth mudbricks was reliably established by identification of the alkane and carbonyl groups present in all the polymer systems used in the experiments (Figures 7.11 to 7.13). The presence or absence of these characteristic peaks were used to determine the FTIR limits of detection for Primal B60A.

FTIR analysis of the surface and centre of Lab Analogues produced using differing concentrations of Primal B60A revealed that polymer was detectable at both the surface and core of the analogue block when using very low dilutions of B60A (Table 8.1). The analogues were produced by mixing 130g of the analogue earth matrix with 30mls of B60A dispersion, which means that at the limit of detection the mass of polymer solids per gram of mudbrick matrix is only 0.000168 g or 0.00045 g cm^3 (Table 8.1). This is a very low detection limit. The UTM tests reported later in this discussion go some way to identifying how idealised consolidations change the strength of earth matrices.

Table 8.1 Mass of B60A solids in analogue substrates.

Dilution Concentration (%)	**Percent Solids in analogue brick (%)**	**Mass solids in analogue brick (g)**	**Mass solids per gram of analogue brick (g)**	**Mass solids per unit volume 50cm^3 analogue brick (g cm^{-3})**
10.00	4.65	1.395	0.01073	0.02790
7.50	3.49	1.047	0.00805	0.02094
5.00	2.33	0.699	0.00538	0.01398
3.75	1.75	0.524	0.00403	0.01047
2.50	1.17	0.350	0.00269	0.00699
1.88	0.88	0.263	0.00202	0.00525
1.25	0.59	0.175	0.00135	0.00350
0.94	0.44	0.132	0.00102	0.00264
0.63	0.29	0.089	0.00068	0.00177
0.47	0.22	0.066	0.00051	0.00132
0.31	0.15	0.044	0.00034	0.00087
0.23	0.11	0.033	0.00025	0.00066
0.16	0.07	0.023	0.00018	0.00045
0.12	0.05	0.017	0.00013	0.00033
0.08	0.04	0.011	0.00008	0.00022

0.06	0.03	0.008	0.00006	0.00017
0.04	0.02	0.006	0.00005	0.00012
0.03	0.01	0.003	0.00002	0.00006

8.3 Surface application of polymer, depth of impregnation

The surface application of 5mls of either polymer solution or dispersion (Section 7.2.1), replicated a consolidation procedure that would likely be used in the field (Koob 1990; Cooke 2008; Peters 2017). Dilutions of 5% and 10% (either v/v or w/v according to whether the consolidant is a dispersion or a solution, provided typical concentrations used to consolidate mudbrick. Results from these tests indicate that consolidation occurs primarily at the surface of the Laboratory Analogue block (Table 7.2; Figures 7.2 to 7.13). Of all the polymer systems and concentrations used in the tests, only 5% w/v Paraloid B48N, B44 and B72 solutions were detectable 1mm below the surface of the Laboratory Analogue (Figures 7.5; 7.7; 7.9). The 10% solutions of these Paraloid solvent polymers failed to penetrate further than the surface of the Laboratory Analogue (Figures 7.6; 7.8; 7.10). All 5% and 10% v/v dispersion systems of Primal B60A, Primal AC-33 and Acrysol WS-24 failed to penetrate the Laboratory Analogue (Figures 7.2; 7.3; 7.4; 7.11; 7.12). As might be expected, a 25% v/v Primal B60A dilution did not penetrate the analogue beyond its surface (Figure 7.13).

These results are of concern, as the consolidant is effectively producing a coating on the Laboratory Analogue, rather than penetrating it. To consolidate just the upper layer of a Laboratory Analogue would realistically require polymer ingress to a depth of 5mm, yet at this depth no polymer was detected for any consolidant. A 5% w/v dilution of B60A has 2.33% solids, representing 0.1165g of polymer in the 5 mls B60A added to the 25 cm^2 surface of the analogue, which if evenly distributed is 0.00233 g cm^{-3}. This is almost 5x higher than the lowest detection level for the FTIR (Table 8.1), so if polymer penetration into the block had occurred is should be detected.

Failure of dispersions to penetrate into mudbrick is confirmed by the analysis of the archaeological samples from Çatalhöyük. For the 20 samples that contained consolidant, polymer was detected on the surface of all of them but was entirely absent 1mm beneath it

(Figures 7.14 to 7.17). At Çatalhöyük Primal AC-33 and Primal B60A consolidants were added in unknown volumes per unit area of mudbrick, which may be more or less than the volume per unit area applied to the Laboratory Analogues. Also, consolidant application at Çatalhöyük involved liberally spraying the mudbrick (Figure 6.1) without recording the quantity of consolidant that was delivered onto the surface. It was also injected or painted onto the mudbrick according to the condition of the blocks and their orientation. The concentrations of consolidant applied are recorded as varying from 2.5% to 50%. Given the wide range of application methods and the quantities that may have been applied to these mudbricks, which are often more porous than the Laboratory Analogues due to the loss of organic binders from their structure, it is more likely that consolidant will have penetrated the mudbrick. It is likely the surface film phenomenon is a reflection of viscosity, rather than particle size. The average pore void at Çatalhöyük is 150-200µm, but ranges from 50-800µm (Aroa García Suárez, personal communication August 2019), which is more than sufficient for Primal B60A 0.03µm particle size.

Çatalhöyük Analogues, produced using ground up mudbrick from Çatalhöyük and consolidated in with 5 mls of 5% Primal B60A, returned results similar to the Laboratory Analogue (Figure 7.19). The consolidant failed to penetrate any deeper than the surface of the Çatalhöyük Analogue. While quantitative data from FTIR is notoriously difficult to produce, due to the challenges of scaling the peaks to known concentrations, Figures 7.20 to 7.22 offer comparisons of peak volumes for Çatalhöyük archaeological samples, Laboratory Analogue and Çatalhöyük Analogue samples, showing strong peaks and large peak volumes for surface consolidant.

The polymer did not penetrate the substrate in any of the tests or, if it did, not at any detectable level. It is challenging to distinguish polymer peaks at low concentrations due to diminished peak heights and the slight shifts in peaks caused by the rough composite substrate. While peak shifts could be considered one of the shortcomings of this methodology, the greater aim was to map consolidation penetration which has been conclusively demonstrated. Also, by extension, peak shifts imply there is no absolute way to tell one aqueous emulsion from another as the distinguishing peaks occur in close proximity. For this research, however, it is irrelevant because none were effective consolidants.

8.4 Interpretation of the pattern of consolidation

The best possible outcome when consolidating a porous substrate is to produce an even distribution of the consolidating polymer throughout the substrate. Mixing polymer dispersions or solutions with mudbrick formers provided an idealised interpretation of consolidation, where the matrix will have consistent overall strength. The polymer forms bridges between particles, cementing them together to create an integrated matrix. During mixing of the analogue constituents, surface tension effects, rheological factors and viscosity will influence the distribution of the polymer. Dispersions offer good wetting ability, as the polar water molecules in the continuous phase readily wet the negatively charged clay components used to produce the Laboratory Analogue (Fernandes et al 2012). Since the polymer particles in the dispersion both repel each other and are attracted to water, they should move easily during mixing and distribute widely within the mixture. Drying coalesces the particles, which have a low minimum film forming temperature of 9^{o}C (Horie 2010). Since the polymer exists in beads of 0.03 microns diameter, their size will hinder their movement towards the surface of the analogue block as the continuous phase evaporates, thereby limiting back movement of the polymer, capillary movement and surface tension effects that aid consolidation, as compared to polymers in solution. These factors explain why the FTIR analysis identified polymer throughout the analogue mudbrick block produced for the limit of detection tests.

The factors that aid distribution of polymer during mixing and drying phases when producing an analogue using an acrylic dispersion, contribute to preventing surface applied consolidants penetrating in-situ mudbrick at Çatalhöyük and the Laboratory Analogues. Since the dispersed phase polymer particles must penetrate the porous matrix of the mudbrick, particle size is a problem, rather than an aid. Also, if separating the polymer particles in the colloidal dispersion relies on the particles carrying a charge, a positive charge will attract them to the clay particles, adhering them to the surface of the mudbrick and its upper reaches, thereby narrowing capillaries. Water has a high surface tension that allows it to readily wet charged surfaces like clays, meaning its movement into the analogue substrate is likely to outstrip the progress of the polymer particles it contains. This will raise the viscosity of the consolidant locally and reduce solution mobility, as concentration increases. There may be chromatographic back movement of polymer particles; as water evaporates, the hydrophilic particles will move back to the surface. Ambient conditions will impact on ingress of consolidant. Rapid evaporation in hot dry climates such as those at Çatalhöyük can increase the concentration and viscosity of consolidants making them 'pool' on the surface of the mudbrick. Low concentrations of consolidant, perhaps at 0.5% to 2% v/v can reduce the effect of evaporation of the aqueous continuous phase, but it will introduce very small amounts of consolidant into the mudbrick (Table 8.1). To introduce a significant amount of polymer into a mudbrick using low concentrations of consolidant, multiple applications must be made and the brick must not be allowed to dry between applications, as the polymer is insoluble in water once set and this reduces porosity and increases hydrophobicity of the block, especially at its surface. Too few polymer beads will mean there are simply not enough of them to coalesce into continuous substantial support.

When contrasting solution polymers with dispersion systems, it is easy to identify why there is greater penetration when using solutions. The solvent surrounds and separates the polymer molecules, which are much smaller and more mobile than polymer beads in dispersions. Solvents are organic, have low surface tension and readily wet surfaces, carrying the polymer molecules into the substrate. Molecules are, necessarily, strongly attracted to their solvent, making chromatographic separation on ingress and egress as solvent evaporates, a distinct possibility. The molecules will have polarity from their carbonyl groups, which will repel the clay particles. If the solvent system dries it is possible to apply more polymer solution with a chance of improving consolidation, as the solvent will dissolve the polymer already in the substrate but this will create higher concentrations of polymer than the concentration that is being applied, changing viscosity and reducing movement of the polymer solution in the mudbrick.

In the tests reported, both dispersion and solution polymers produced a skin on the analogues. There was no effective consolidation. Extrapolating this to field contexts is a sobering thought, as all the evidence of laboratory and field-testing points to there being no effective consolidation of the mudbrick substrate. It may be that different application methods are required, whereby the mudbrick is pierced and consolidant is injected in a regular pattern. Any option to use solutions is ruled out in many field contexts. For example, at Çatalhöyük there is the cost of the solvent (typically acetone or similar polar solvents) to consider, as well as its availability, evaporation rate in the hot Turkish climate and health and safety of the solvent fumes with excavations taking place. The reality is that dispersions remain the only viable choice, but 5% w/v dispersion systems fail to deliver any in depth consolidation. Extensive further work on consolidation procedures and the impact of variables such as climate need to be investigated.

8.5 UTM strength testing

Reporting compression testing according to the amount of force applied at breaking point reveals the expected result that the idealised consolidations, where the polymer was introduced into the analogue when it was formed, required the highest application of force to break (Table 8.2). A similar pattern emerges when the data is considered as a function of deformation distance before breakage, the Mix5% and Mix15% samples deform most before breakage, indicating they are less brittle than the consolidated samples (Table 8.3). Interestingly, the 5% v/v Primal B60A mixture required the greatest force to break; almost 3 times the force required to break the 15% mixture and it deformed more, demonstrating its toughness. This might be considered to be an unexpected result, as there is 3 times as much polymer in the Mix15% and it is reasonable to expect this would be a stronger mixture that a Mix5%. This extra polymer may have created a more brittle analogue, as the compressibility of the Mix15% before breaking is also less than the 5%Mix, perhaps reflecting increased toughness in the Mix5%. Alternatively, the outcome may be due to uneven distribution of polymer within the mixture from the influence of various physical factors during the mixing such as viscosity and surface tension.

Table 8.2 Average compression FMax descending order of force (Newton).

Sample group	**Notation**	**Group and dilution volume**	**$\bar{x}$ F_{max} N**	**$\bar{x}F_{max}$mm Compression**
1	Mix5%	5% Mix (30mls)	14500	4.8
2	Mix15%	15% Mix (30mls)	5080	2.9
7	50_25	Arid 50°C, 25% RH (4mls)	1450	1.7
12	B44	5% Paraloid B44 (5mls)	1380	1.7

4	AP 15%	15% Primal Mass (3mls)	1220	1.8
5	AS 5%	5% AS (5mls)	1120	1.4
3	AP 5%	5% Primal Mass (9mls)	1080	1.8
11	UT	Untreated	1050	1.5
10	10_25	Continental 10°C, 25% RH (4mls)	1030	1.6
6	AS 15%	15% AS (5mls)	991	1.6
9	10_75	Temperate 10°C, 75% RH (4mls)	951	1.6
8	40_90	Tropical 40°C, 90% RH (4mls)	792	1.8

Table 8.3 Average compression FMax descending order of deformation distance (mm).

Sample Group	**Notation**	**Group and dilution volume**	**$\bar{x}$ F_{max} N**	**$\bar{x}F_{max}$mm**
1	Mix5%	5% Mix (30mls)	14500	4.8
2	Mix15%	15% Mix (30mls)	5080	2.9
4	AP 15%	Primal Mass 15% (3mls)	1220	1.8
3	AP 5%	5% Primal MassP (9mls)	1080	1.8
8	40_90	40°C, 90% RH (4mls)	792	1.8
7	50_25	50°C, 25% RH (4mls)	1450	1.7
12	B44	5% Paraloid B44 (5mls)	1380	1.7
10	10_25	10°C, 25% RH (4mls)	1030	1.6
6	AS 15%	15% AS (5mls)	991	1.6
9	10_75	10°C, 75% RH (4mls)	951	1.6
11	UT	Untreated	1050	1.5
5	AS 5%	5% AS (5mls)	1120	1.4

Considering the range of results for the break point force and compression values of all samples in a test group (Figures 8.1 and 8.2), reveals the Mix5% and Mix15% have the broadest ranges. The box plots clearly show the untreated Laboratory Analogues have consistent results and hence good reproducibility as analogues. Consolidated sample groups showed no significant difference in either force or extension values at the break point (Figures 8.3 and 8.4). Overlap between force and extension ranges at break point for the 10 samples in each consolidation group and the untreated Laboratory Analogue means that it is not possible to state that any of the consolidation methods increase the strength of the Laboratory Analogue beyond its unconsolidated values. This is clearly evident when the FMax values for all samples are considered as a scatter plot (Figure 8.5). All consolidation tests and the untreated Laboratory Analogue cluster into a group. Close examination of the range of force required to break all consolidated and untreated Laboratory Analogues reveals breakage extending over a range of 600-1700 Newtons (Figure 8.6). About a third of the samples have a breaking force greater than the untreated Laboratory Analogues but there is no set pattern, as no one group of test samples lies above the highest breaking point value for the untreated Laboratory Analogue (Figure 8.6).

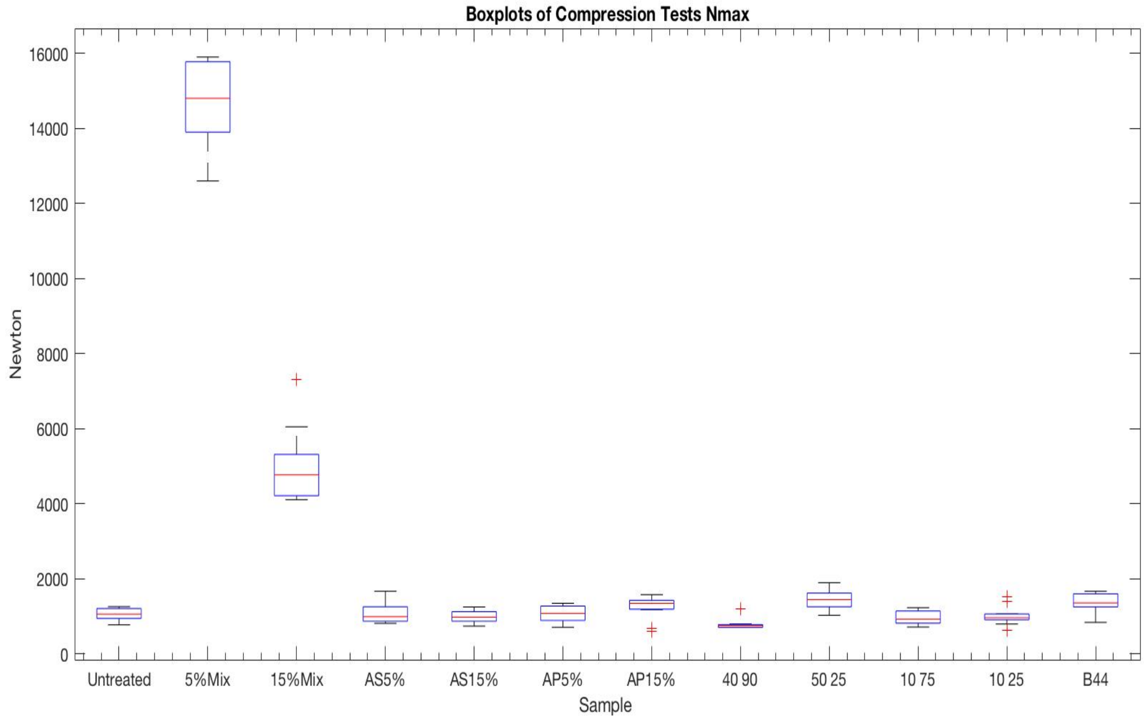


Figure 8.1 Quartile distribution of all compression test groups at Nmax, point of force at sample breakage.

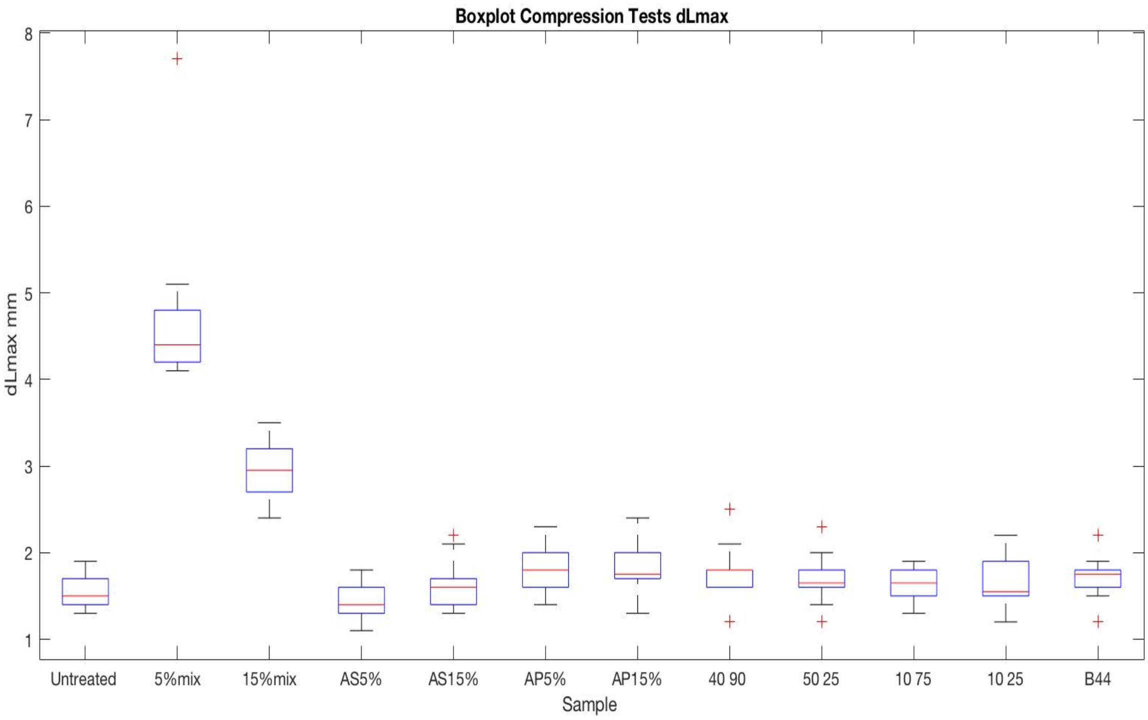


Figure 8.2 Quartile distribution of all compression test groups at dLmax, point of distance at sample breakage.

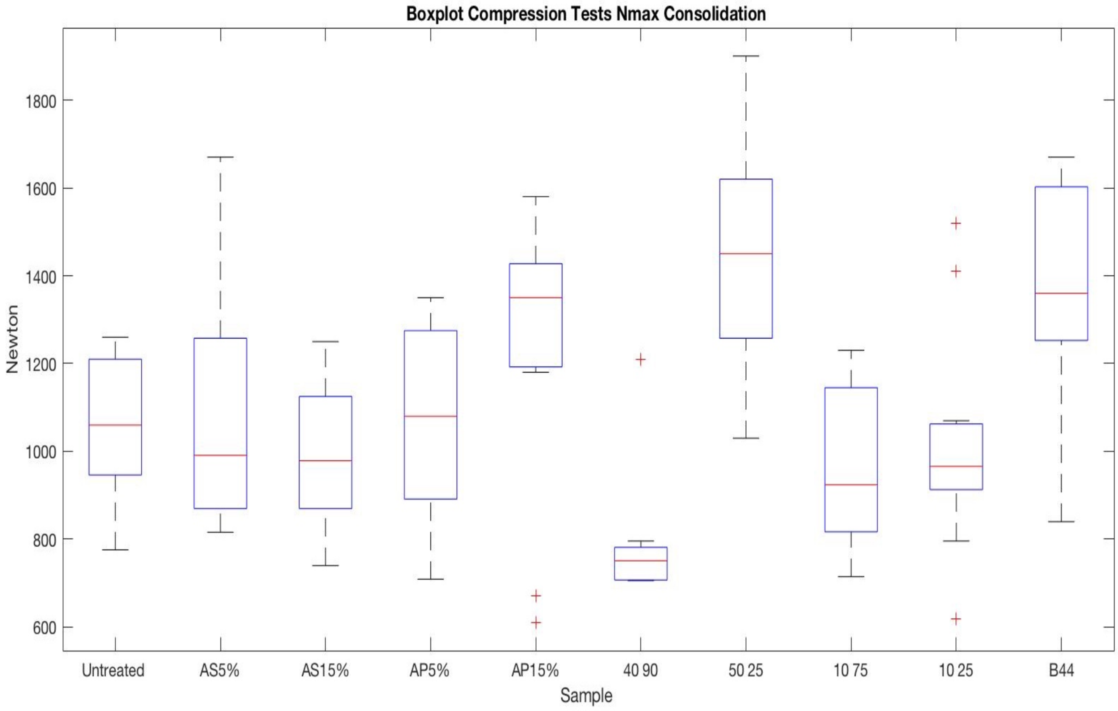


Figure 8.3 Quartile distribution of untreated and surface-treated compression test groups, at Nmax, point of force at sample breakage with the 5% and 15% Mix samples omitted.

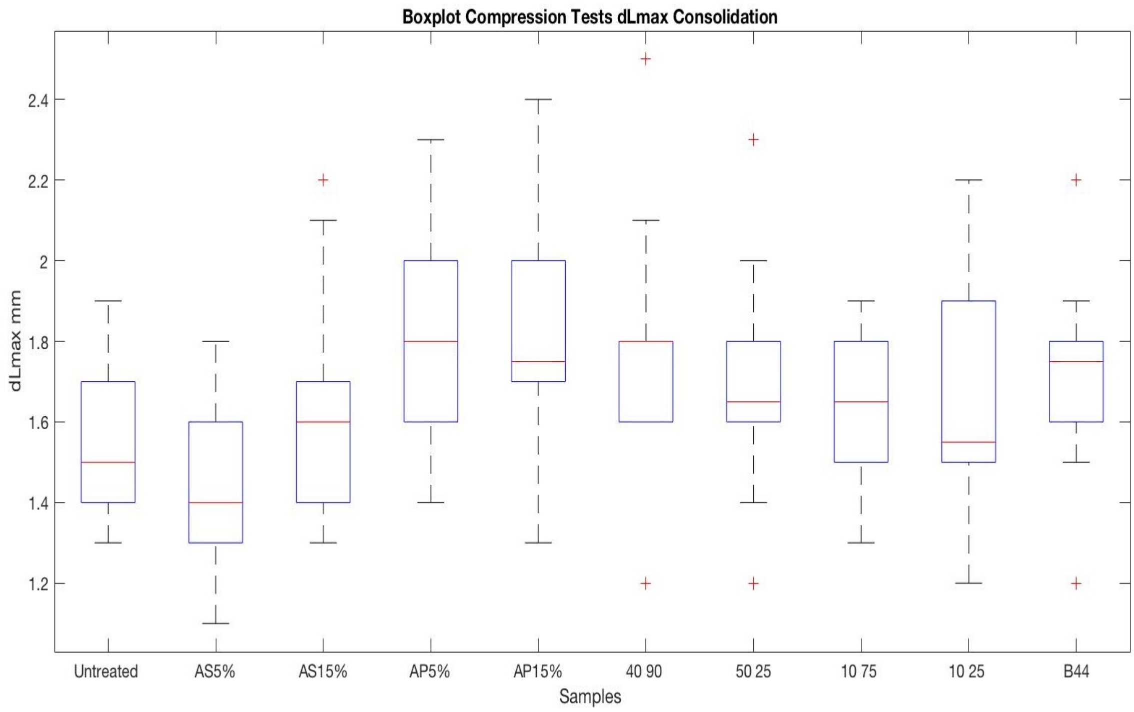


Figure 8.4 Quartile distribution of untreated and surface-treated compression test groups, at dLmax, point of distance at sample breakage with the 5% and 15% Mix samples omitted.

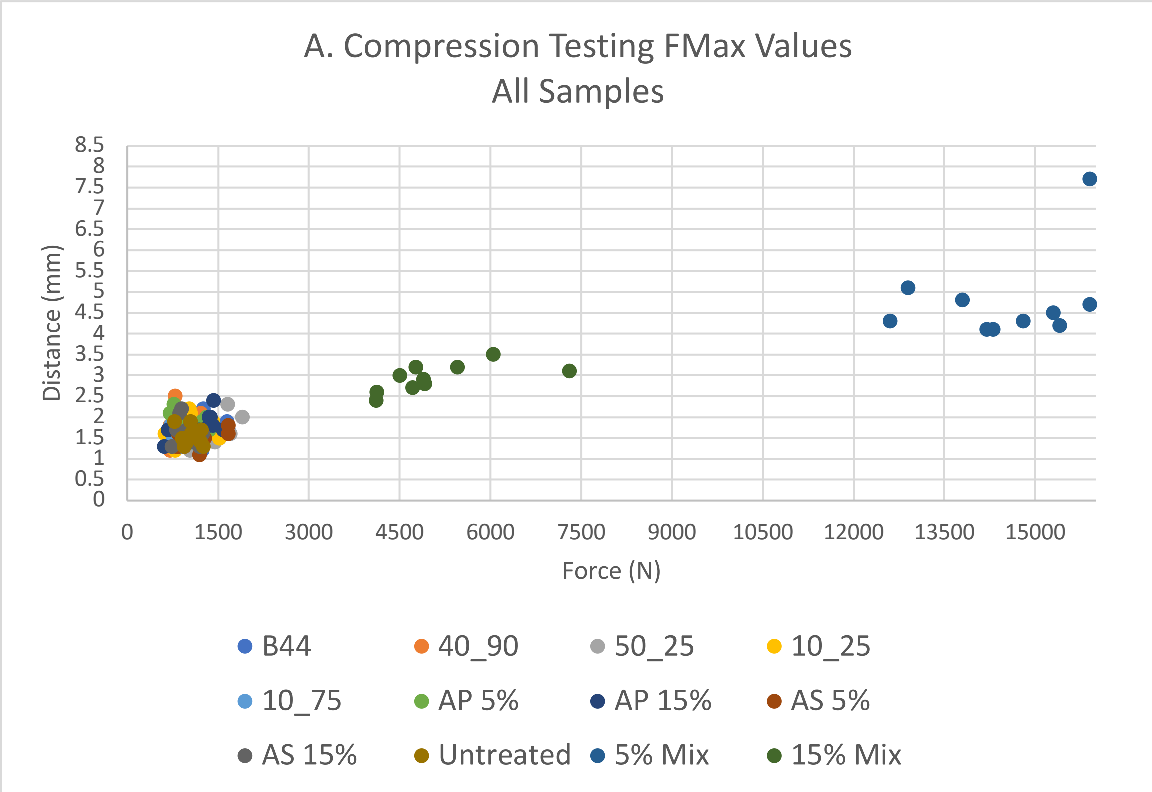


Figure 8.5 Scatter plot distribution of deformation results for every sample compressed by the UTM, dLmax distance over Fmax measurement.

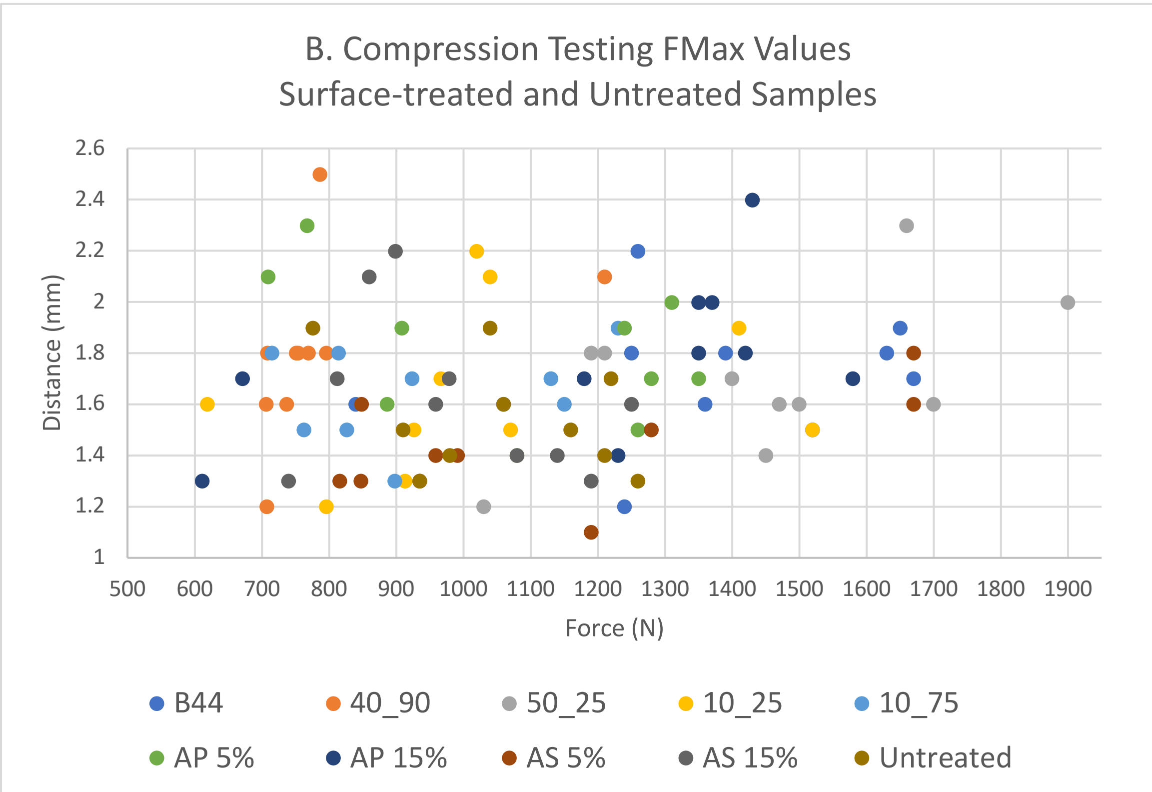


Figure 8.6 Scatter plot distribution of deformation results for the untreated and consolidated samples compressed by the UTM, dLmax distance over Fmax measurement.

Controlling conditions during drying to reflect differing climatic conditions that might be experienced on site, did not reveal any significant differences or noticeable patterns (Figure 8.7). Although it is tempting to suggest the low relative humidity and high temperature drying conditions (50°C and 25%RH), appear to offer a grouping that requires a higher range of force for breakage to occur. These conditions would produce rapid drying of the sample, possibly reducing any backward movement of consolidant.

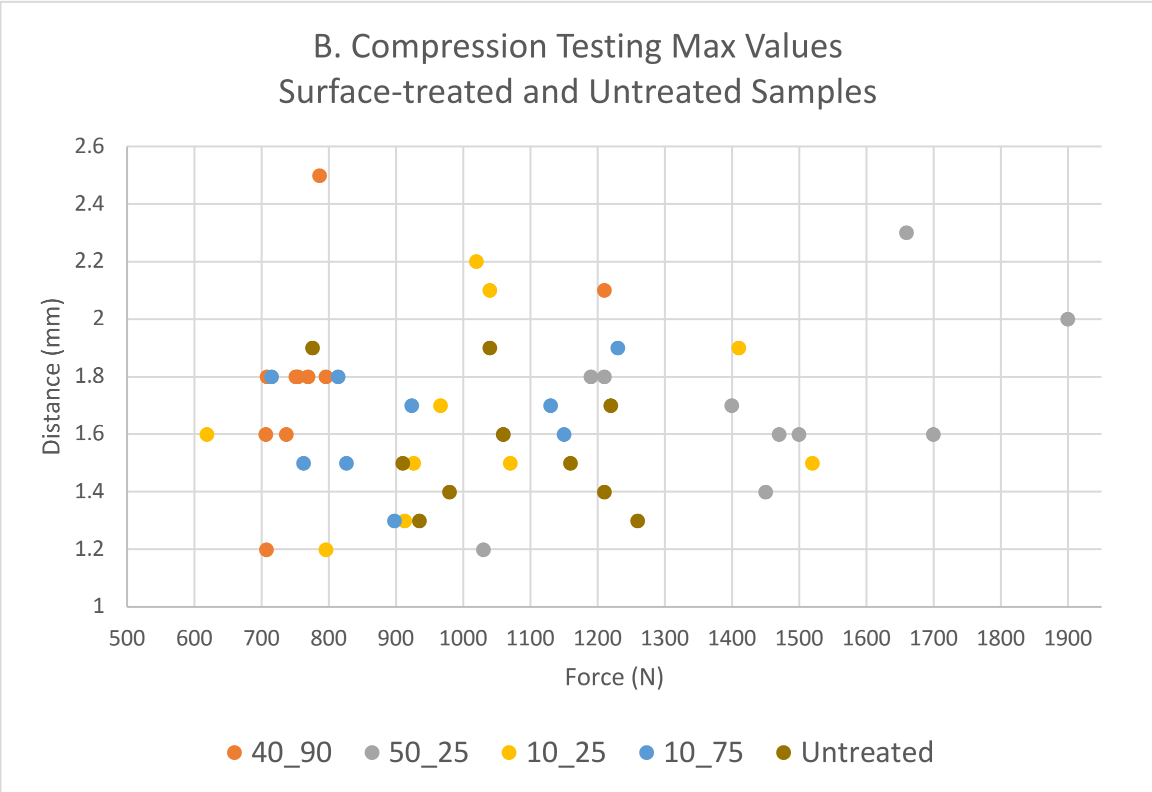


Figure 8.7 Controlled drying consolidations and Laboratory Analogue untreated samples.

8.6 Perceptions of conservation laboratory practice and in the field

Ideological tenets of conservation philosophy such as reversibility, authenticity, and ascribing equal value to all things, are crucial to creating a dialogue about the conceptual value changes that conservators can make through intervention (Cane 2009). These issues are true across the heritage sector, however, when practically applied in the archaeological field these principles can be difficult to strictly follow. Often discussions on which element (visitor/material/analysis) to privilege creates complex issues for the preservation of archaeological sites. The growing discourse on values-based practice within conservation

(Avrami et al. 2000; Muñas-Viñas 2005), which has implicit and explicit ramification for how interventions are carried out, and how conservators rationalise their work. Current sector ethos is to balance current research, access, and planning for a sustainable future in a respectful and authentic manner (Avrami et al. 2000). Undifferentiated respect becomes even more difficult if the needs of present and future audiences are considered, and further complicated if real world concerns about budgets and work priorities are included (Ashley-Smith 2018). A values-based approach suggests that conservation should seek to sustain and enhance heritage significance rather than arrest physical change, and value judgments underlying conservation decisions are made explicit (Cutajar et al 2018).

In practice, laboratory conservation practice offers greater control and fewer variables over experimental design and material behaviour. Treatment methodologies can also vary from laboratory recommendations to field practice, which, in this author's experience, can happen for a myriad of reasons. For example, the use of polymers for consolidation on a large scale, small laboratory experiments cannot reflect all the real-world variables. Other occurrences, like a breakdown in communication, can happen, e.g. the application method was not specified, communicated, or the individual(s) in the field made modifications to the treatment to meet other ideas/needs. Alternatively, the treatment was not fit for purpose, e.g. the polymer was unsuited to the environment, treatment required a solvent too volatile to use in the field, or the polymer performed differently than in laboratory experiments. Integrating methods for treatment review and making them part of the conservation ethos needs to part of responsible conservation practice.

The environment in particular, is one way in which conservators must adapt in the field and influences the success of a treatment outcome. While laboratory research can model sophisticated environmental conditions, in practice, it still falls short of the environmental variability faced by in-situ heritage. Furthermore, there are countless material studies carried out in laboratories, which do not take the ambient conditions into account, and while that can be less of an issue for objects in stores and showcases, it can be detrimental to heritage kept outdoors.

Ideas of reflexivity and developing approaches to heritage interpretation are significant part of the ethos of the Çatalhöyük Research Project. In 'The Conservation of an Excavated Past', Matero (2000:71) writes 'reflexivity as a methodological approach in the production of knowledge takes its primary position from the contextualization of the problem rather than the superimposition of positivist, empirical models. Nevertheless, any methodology depends on all the interrelationships between theory and practice as expressed through the intersection of principles, practices and procedures.' The context of laboratory treatments is arguably different to treatments carried out in the field. This is not to say laboratory and field conservation research are oppositional, they can complement one another when properly contextualised. How the research questions are asked and reflected on are essential to applying laboratory research within the field. For archaeological sites, without questioning *why* as well as *what* in the conservation of earthen ruins it is possible end up with the correct answers to the wrong questions (Matero 2015:222).

8.7 Implications for practice at Çatalhöyük

These results, along with climate data from the site, allow consideration of more environmentally compatible conservation interventions to treat the in-situ archaeology. Primal B60A has been replaced with Paraloid B-44 (methyl methacrylate and ethyl acrylate copolymer), a thermoplastic acrylic resin with a Tg of 60°C. While Paraloid B-44 is more commonly found in metals conservation, it is more suited to the environment at Çatalhöyük as it will not soften in the 50°C heat under the North Shelter. Furthermore, Paraloid B-44 is immiscible in water, an acetone:ethanol mix is used which does not cause problems of swelling and shrinking within the clay matrix. The use of Paraloid B-44 with solvents is a more expensive treatment and requires increased personal protective equipment consideration. However, since the introduction of this polymer in 2015, there has been a decline in the frequency of retreatment of the in-situ archaeology, which was common with the Primal systems. This reduced application is interesting, as the results of this research demonstrate that Paraloid B-44 still disperses only shallowly into the substrate. Paraloid B-44 is used both as a consolidant in low concentrations (e.g. 5%), as well as part of the treatment of cracking surfaces in a more viscous concentration (e.g. 10%).

Due to a lack of an effective polymer options consolidation of the archaeological surfaces has been significantly scaled back. However, conservation interventions are still necessary to treat the earthen architecture. Cracking surfaces are still a significant problem and Paraloid B-44 is an effective part of the treatment strategy. Before 2014, cracking surfaces were treated with hydraulic lime-based grouts mixed with sand and Primal B60A; these were developed and employed for consolidating voids and cracks in walls and detached plasters (Matero 2000). Before the construction of the North Shelter, this grouting mixture performed as designed, but since the shelter construction, the polymer can no longer successfully be used in the summer months, and the high temperatures cause problems with the lime setting. The fills also had to be in-painted to blend into the surrounding architecture; otherwise, they were a highly visible grey colour (Figure 8.8). A new methodology was sought for a more stable solution that required less treatment time. After testing during the 2014 season, a mixture of 10% Paraloid B-44 w/v in 50:50 acetone;ethanol, perlite, and soil proved to be a suitable solution (Lingle 2014). As it is erroneous to think that a superficial repair to the wall will provide structural support, the fill acts to stabilize the fissure and prevent external damage from wind abrasion. The rationale behind this mixture is the perlite acts as a permeable bulking agent, so moisture can still preferentially exit through the crack, the Paraloid B-44 provides tough, but flexible cohesion and the soil blends the fill to the surrounding wall. Results from this research clearly show how mixing polymer into a grout significantly increases strength. This can be expected to occur with lime plaster, along with the process of conversion for $Ca(OH)_2$ to $CaCO_3$ adding cohesion to the matrix.

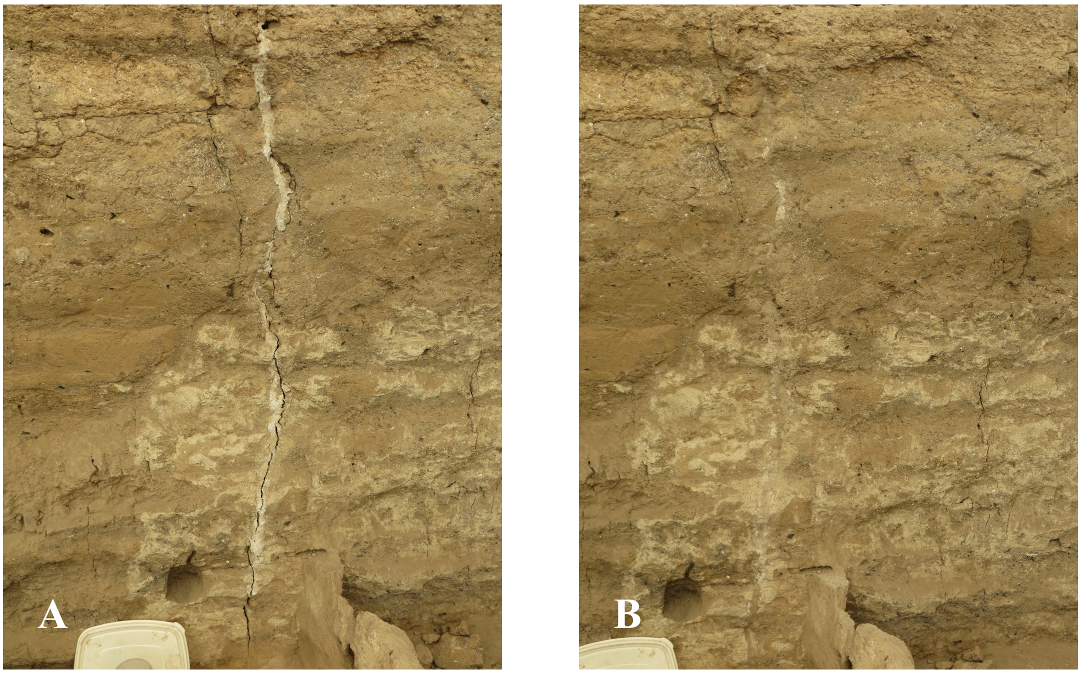


Figure 8.8 Comparison of fissure repair methods. A. Lime, sand, and Primal B60A fissure repair carried out in 2011. B. Paraloid B-44 and soil fissure repair carried out in 2016. Photographed by the author.

In 2013 a small number of tests were carried out to create undercutting supports for walls F. 221 in Space 90 and F. 231 and 230 (southern portion) in Building 5. The rationale for these supports is to manage deterioration by creating an area for preferential deterioration. As the walls themselves were deteriorating from the base up, it stood to reason that limiting the upward migration of moisture and soluble salts would extend the lifespan of the walls. This type of repair is a modification of a traditional building technique used on earthen structures (Illampas *et al.* 2013). These supports are first lined with geotextile, and then rammed earthen composed of chaff and perlite is built up in the void under the wall. Tests showed that not only does this impede the undercutting, it also slows the deterioration of the wall (Figure 8.9).

Figure 8.9 Feature 231 in Building5. A. Before undercutting repair in 2013. B. At the end of 2014 season. C. At the end of the 2017 season.

The Çatalhöyük Research Project is moving into an exciting new phase when the current excavations will come to an end, and a long-term conservation strategy will need to be designed and implemented. The new research teams are opening excavation outside of the permanent shelters. This change in research area leaves the currently exposed archaeology as part of an archaeo-park, which the local government plans to expand in the coming years. The reactionary conservation strategy practised at the site worked with the actively excavated areas but has proven unsuccessful in areas of long-term display. The more environmentally sympathetic treatments taking place over the last several years are proving promising, but further investigation is critical.

8.8 Sector Impact

8.8.1 Perceptions and evidence

The application and perception of consolidation is not limited to earthen architecture. It is a treatment applied across all materials in conservation with hugely variable degrees of understanding of processes and their effects. Consolidation is, by definition, to solidify and labelling a material as a consolidant suggests that the material can solidify an object or structure. In many instances, this terminology may not be a misnomer but the lack of studies employing polymer mapping within the conservation literature means this cannot be proven. The findings here may not be an isolated occurrence of consolidation treatment failure.

An international survey of conservation practitioners working with architectural tiles (Mendes et al. 2015) cites consolidation and bonding with acrylic polymers (primarily Paraloid B72 and Primal AC-33) as the preferred method across respondents. The survey also reports that 39% of respondents use observational effectiveness monitoring, with only 19% following up with some level of laboratory analysis. By looking at some broader trends in identifying gaps in conservation practice, the potential for empirical practice become more evident. A survey of international conservation practitioners working in museums and at sites in The Near East (Fitzpatrick 2016) presented some alarming trends. Nearly half of the respondents (47%) note that conservation treatment records are not provided and 72% offer no further treatment or analysis recommendations. The evidence from these studies considered alongside the results of this research underline the need for better-informed practice driven by greater investigation of treatment effects.

The conservation of waterlogged wood provides an insight into the value of investigative approaches. Over a century of treatment, evaluation and research by a wealth of workers who developed a collaborative international working group arrived at a procedure that can be tailored to the condition of artefacts and applied with a degree of confidence regarding outcomes (Hoffmann 2007). Continuous feedback to the sector and monitoring of treated objects and structures updates the conservation community regarding problems and refinements and drives research agendas (ibid). The complexity of consolidation treatments and the uncertainty of their effectiveness calls for a similar approach to developing understanding and tailoring processes to improve long-term survival prospects of heritage materials.

8.8.2 Research and practice in earthen architecture

Improved links between research in the lab and efforts in the field are suggested by many in the sector, further highlighting the need for enhanced dialogue among practitioners and scientists to address issues related to earthen construction and conservation (Avrami and Guillaud 2008). Particularly relevant to this is the importance of follow-up monitoring and evaluation of conservation interventions, as demonstrated by this PhD research. Conservators need to know what the long-term successes and failures are in order to learn from them. Avrami and Guillaud (2008) also emphasise the inextricable link between conserving earthen heritage and promulgating earthen building. Much of the constructive culture of earth lies in its continued evolution as an architectural form and tradition, forging connections between conservation and new construction remains an important task, both in research and practice (ibid). Central to this is the role the climate plays in the materials conservators treat, and the materials they use.

8.9 Future research

As with any research, there is an opportunity for further research and conceptual exploration. This study demonstrates the potential to apply this method to investigate the consolidation of earthen substrates further. Silicate systems, for example, which other studies have concluded to be an effective consolidant would be exciting to interrogate, along with the impact of surfactant use. Application is another area which would benefit from further exploration. Methods of spraying or injecting the consolidant have yet to be tested with this methodology and, while they were initially excluded, it would be interesting to revisit these variables as reflections of sector practice. While it might be simple to focus on the surface application being the culprit for poor penetration, other methods such as injection would still experience difficulties with dispersion which could lead to other deterioration issues (i.e. sheering and cracking). One way to expand the methodology is to incorporate further climate modelling. Climate can have a significant impact on the efficacy of a treatment, as well as depend on the nature of treated material. Earthen materials are greatly impacted by moisture, examining the relationship of climate and polymer performance can elucidate how the polymer performs when used both within and outside of the manufacturer's guidelines.

Most material testing is carried out in a laboratory atmosphere of approximately 20°C and 35% relative humidity if documented. Field conservators often face challenging climates very different from that of a laboratory. Annual climatic ranges can further complicate the matter across a given site (i.e. summer to winter). Temperature can impact both initial curing and long-term stability. High levels of relative humidity can also influence polymer performance, typically becoming less reliable with higher levels of moisture in the air. By utilizing climate data and incorporating them in this methodology, questions regarding in atmosphere and glass transition (Tg), how humidity impacts curing, and the performance of multiple coats of consolidant can be investigated.

Further field testing and expanding this analytical method to other historically treated sites and polymer systems could be an interesting avenue of research, examining other instances of a polymer not performing as expected by conservators. It would benefit the sector to look at these types of past treatments and determine if the interventions worked as expected. This broader study would provide additional opportunity to collect data on perceptions of consolidation and material performance.

9 Conclusion

At any earthen site, the selection of a preservation treatment should be the result of careful study of the environmental conditions and the physical, mechanical, and chemical properties of the materials used in the architecture, as well as the properties of potential repair materials drawn from both traditional and modern sources

Oliver 2000

9.1 Consolidation in practice

Linking the results of this study to field practice identifies that long held perceptions about the outcomes of consolidation are inaccurate. While the consolidation methodology used in the experimental work reported here is just one approach to applying consolidants, it is typical of how consolidation may be carried out. Penetration of polymer into the analogue universally failed and there was no strength increase in analogues post-consolidation, irrespective of whether the polymer system was solvent or dispersion based. However, results show that if total integration of the polymer into the matrix of the analogue can be achieved, strength gains are significant.

While the benefits of an effectual consolidation process are documented and achieved in other sectors of conservation (Ling et al. 2010), how can practices be adapted and refined to achieve this in the field with earthen heritage? Carrying out more studies looking at lower concentrations of polymer, with differing application protocols, applied to a range of analogues of differing physical properties is a way forward to determine how effective consolidation could be and to identify best practice. These investigations must also consider the specifics of the site and substrate. At any earthen architecture site, decision-making in choice of conservation methods and materials must be the result of a nuanced understanding of prevailing environmental conditions and the chemical, physical and mechanical properties of the construction materials. In the shifting dynamic of changing climates and with ongoing complications of human activity, long-term treatment success must be analysed and reviewed at feasible intervals. This research offers a methodology by which practitioners can evaluate treatment options in conjunction with preservation philosophy and practical considerations of site management.

9.2 Sustainability

The results of this study are clear that the application of Primal B60A in the context of a consolidant is not suited to use on earthen architecture; however, some broader sector implications can be taken away from this study. Interventions need to be meaningful and fit for purpose. Treatments need to be carried pragmatically, but also to be done reflexively and scientifically. Observing intervention outcomes is not the same as measuring them. Perceptions can be wrong even with great knowledge and the best intentions.

A more reflexive approach in the professional community is desperately needed, treatment reports which were not effective need to be seen as academically valid - when and why interventions do not succeed are equally crucial to moving the profession forward. Scientific research is one aspect of broader planning for heritage management and the strategic advancement of earthen architecture (Avrami and Guillaud 2008) and sector practice at large. A part of sound scientific research is reviewing current findings to pose new questions, which is difficult when the larger scope of research is fragmentary. A critique of both field practice and laboratory analysis is that they are both forward-looking and have limited timescales – which is a very practical issue. Science and technology are moving at an ever-faster pace, and with them has come access to information and materials within conservation along with the impetus to create modern treatment strategies. Time needs to be taken to look back at what has been done as the field moves forward.

In the case of archaeological earthen architecture, there needs to a wider discussion of breaking with some of the tenets of conservation, specifically reversibility and authenticity. If an earthen site is deemed significant enough to warrant the investment to make it widely accessible and not rebury, it is this authors opinion; there also has to be a pragmatic acceptance of how this site is preserved and managed. In terms of consolidation, no treatment is truly reversible, ethyl silicate systems are entirely irreversible, and to remove other polymer systems would case the architecture to disaggregate. While the earthen structure is still re-treatable, the question then becomes 'to what end?' As for authenticity, Muñoz Viñas (2012) argues 'an object remains a genuine object whatever its state, as long as it has a physical existence.' While such a broad definition can be problematic, it does highlight the need to define what is being conserved. In the case of archaeological earthen architecture, conservation is being carried out for the buildings to be on display, so all else being equal the structural and aesthetic qualities of the structures are what needs to be preserved. Arguably, more interventive measures such as the structural consolidation discussed in Chapter 3, are more fit for purpose than polymer application in the case of earthen architecture. In the case of Çatalhöyük, Pye (2006) discussed the polymerisation of Building 5, asking If the 'conservation would eventually destroy the building's authenticity?' As the discussed in this PhD, the polymer system was a contributing factor to the deterioration of the buildings at Çatalhöyük, while B. 5 is not destroyed it no longer holds the same aesthetic qualities or is as structurally sound.

Furthermore, except in unique situations such as the survival of earthen mural paintings or reliefs at archaeological sites, most earthen ruins have lost their intrinsic surfaces. These outermost surfaces are critical to the stability of earthen walls. Unlike most masonry ruins, they need surface protection to resist loss and collapse. As a result, the archaeological value of earthen ruins in-situ has more to do with their presence in the landscape and the survival and legibility of larger architectural attributes and construction evidence (Matero 2015). The evidence argues for more interventive rather than remedial treatments, as is the case with the justification for installing sacrificial earthen caps on wall tops or building shelters (ibid). A broader range decisive but no less reversible methods of protection are imperative (Buccellati, 2006).

9.3 Reflections on practice

Architectural conservators and conservation scientists continue to try to find remedial treatments that will improve the moisture sensitivity and cohesive strength of exposed earthen ruins without completely concealing or damaging the original material. This objective, common to conservation thinking, is perhaps flawed when applied to earthen materials (Matero 2015: 209). Rather than search for an intervention which may never be possible, there is an argument for more efficient resource management across the heritage sector. Preventive conservation at archaeological sites includes a broad range of measures, aimed at passively mitigating deterioration. For archaeological sites, preventive conservation is the act of reducing, minimising or preventing future loss. Preventive conservation excludes actions that intervene on the structure and materials of the site, a challenging requirement when accounting for open environments and large-scale infrastructure (Henderson and Lingle 2018).

The implementation of digital technologies across the heritage sector has created an important opportunity for preventative conservation work. For complex sites, like earthen heritage, digital modelling provides a means for study, monitoring, and engaging with heritage in a sustainable manner. For instance, multiple 3D scans can be used to reconstruct archaeological phasing (Berggren et al. 2015), overlaid to look quantitively at wall attrition (Campiani et al. 2019), or used to develop publicly available virtual reality experiences (Barceló 2000). Once sites are exposed, studied, and scanned, one option is to accept current preservation limitations rebury the site. While reburial protects the original fabric of a site, it does limit access making it a contentious preservation measure. When reburial is being considered as an option for the preservation of an excavated site there are numerous considerations that need to be taken into account if the values of a place are not to be compromised and stakeholders alienated (Demas 2004: 137). However beneficial reburial may be from a conservation perspective, it is generally viewed with scepticism or disfavour by those with legal authority over a site, and by those stakeholders who want access to the site for study, education or money-making (Ibid).

Site significance and risk management play a large role in creating the framework around archaeological sites. The tangible and intangible values of the site must be assessed along with the associated risks, to ensure that both the material substance and the associated values are afforded protection compatible with current and future use (Paolini et al. 2012). Each decision made has an inherent level of risk. Risk of losing knowledge, risk of treatments going wrong, risk of shifting ethics, and the risk of doing nothing. While risk is used as a determinant of ethical conduct (Ashley-Smith 2018), it is not insular to conservation. Conservators typically advocate for prolonging the life of an object or place, it is the larger contextual discussion with other stakeholders that ultimately decide the desired outcome for heritage materials. Understanding relevant risks to heritage aids in these discussions, and what options afford the greatest opportunity relative to the risks involved.

The reality is that often there is no 'best' choice, as complex ethical variables have usually comprised - or been compromised by - other variables in the decision chain. In the archaeological field particularly, limitations on resources is a significant factor in the decision-making process. There is also the reality of treatments or collaborations not going to plan, and the residual implications for these failings. In an excavation environment, collaboration, communication, and innovation are demanded to ensure that outcomes meet the goals of individual units and the overall project whilst adhering to an ethical framework that can account for both conflict and the unknown. Within conservation, there is a current trend in the wording of codes of conduct and ethics that avoid explicit definitions practical interventions (Ashley-Smith 2018), creating an imprecise paradox in conservation practice: is an intervention justified because it is ethical or ethical because it can be justified.

9.4 Challenging conservation assumptions

The findings of this research project challenge concepts which have long been held by conservators. In the absence of data from any qualitative or quantitative study, conservators must use the evidence of their own eyes and their experience when evaluating treatments, particularly when working in the field. On application of a consolidant in a medium which is seen to penetrate the substrate, the assumption is that the polymer is also penetrating the substrate. Logically, this is particularly likely when the substrate is known to be porous. This assumption has prevailed at Çatalhöyük over many years and for a succession of conservators. Yet this study shows that, despite best efforts by experienced conservators and multiple applications over time, all that has been achieved is the creation of a polymer skin which is unlikely to have improved mechanical properties of the heritage architecture. The perception that the structures have been 'treated' is misleading and has the potential to deflect attention from material which remains in need of interventive and preventive conservation.

Publication of this research will issue a call to the profession to examine assumptions about treatments made on the basis of common sense, logic and observation. All of these are fundamental to conservation practice and are a major component of professional training.

However, a more complete picture is not revealed until the outcomes of treatments are examined via analysis and evaluated by long-term observation of performance in-situ.

9.5 Outcomes and impact

The outcomes of this PhD have already impacted on sector practice. In the specific case of Çatalhöyük, the results of this study are being used to inform improved conservation management and treatment strategies at the site. Consolidation is now limited to painted wall plasters that will ultimately be removed and taken to the local museum; the routine practice of spraying a consolidant on walls post-excavation has been eliminated. The material choices and interventions employed at Çatalhöyük are more suited to the environment, having demonstrated to perform in context. This study provides a solid foundation for future conservators taking on care of the site. With documentation by past conservators and other researchers, this project can address an issue within conservation practice and challenge the perception of how a specific material performs. Using this information, the conservators at the site have successfully begun incorporating materials more sympathetic to the environment into the conservation program for the in-situ archaeology.

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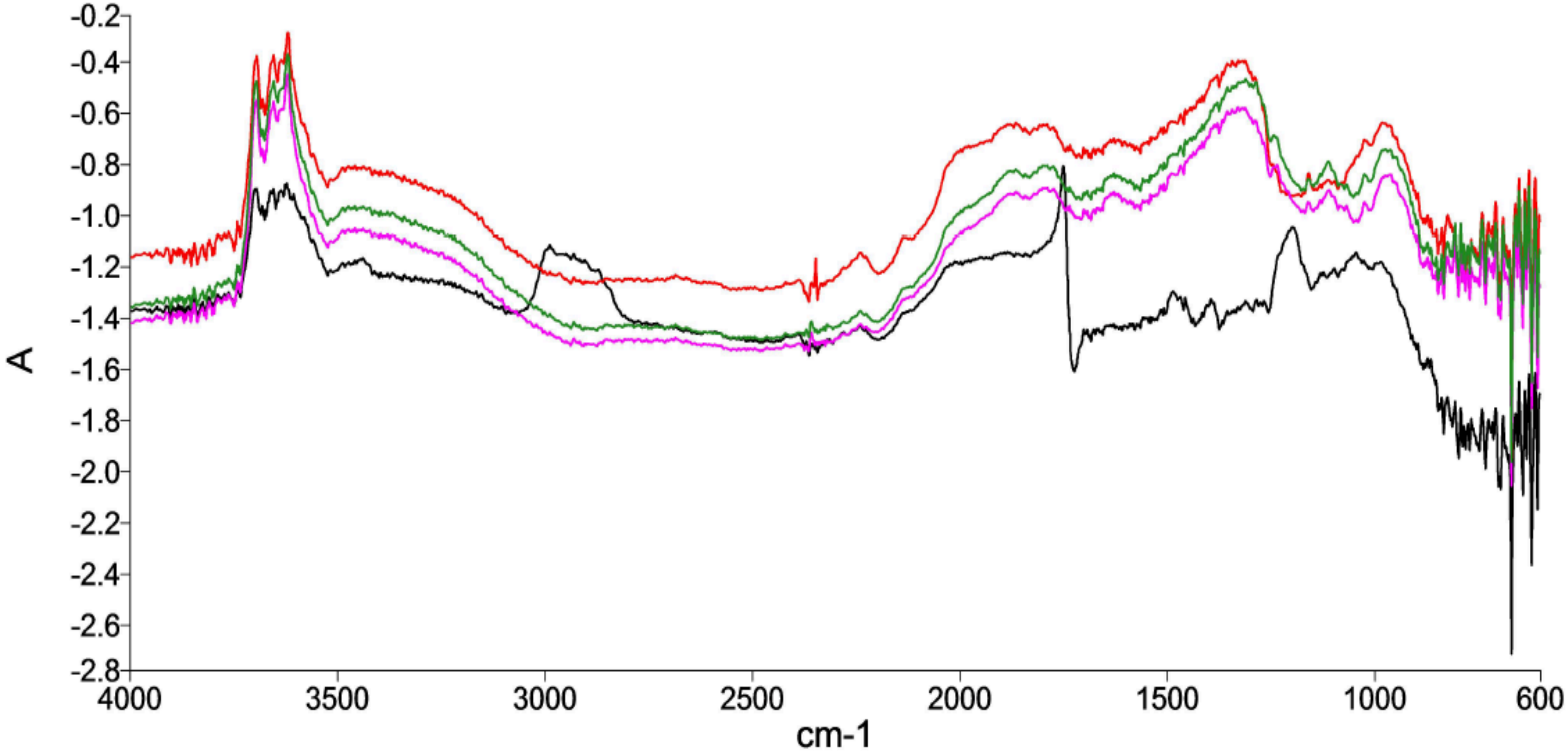
Appendix

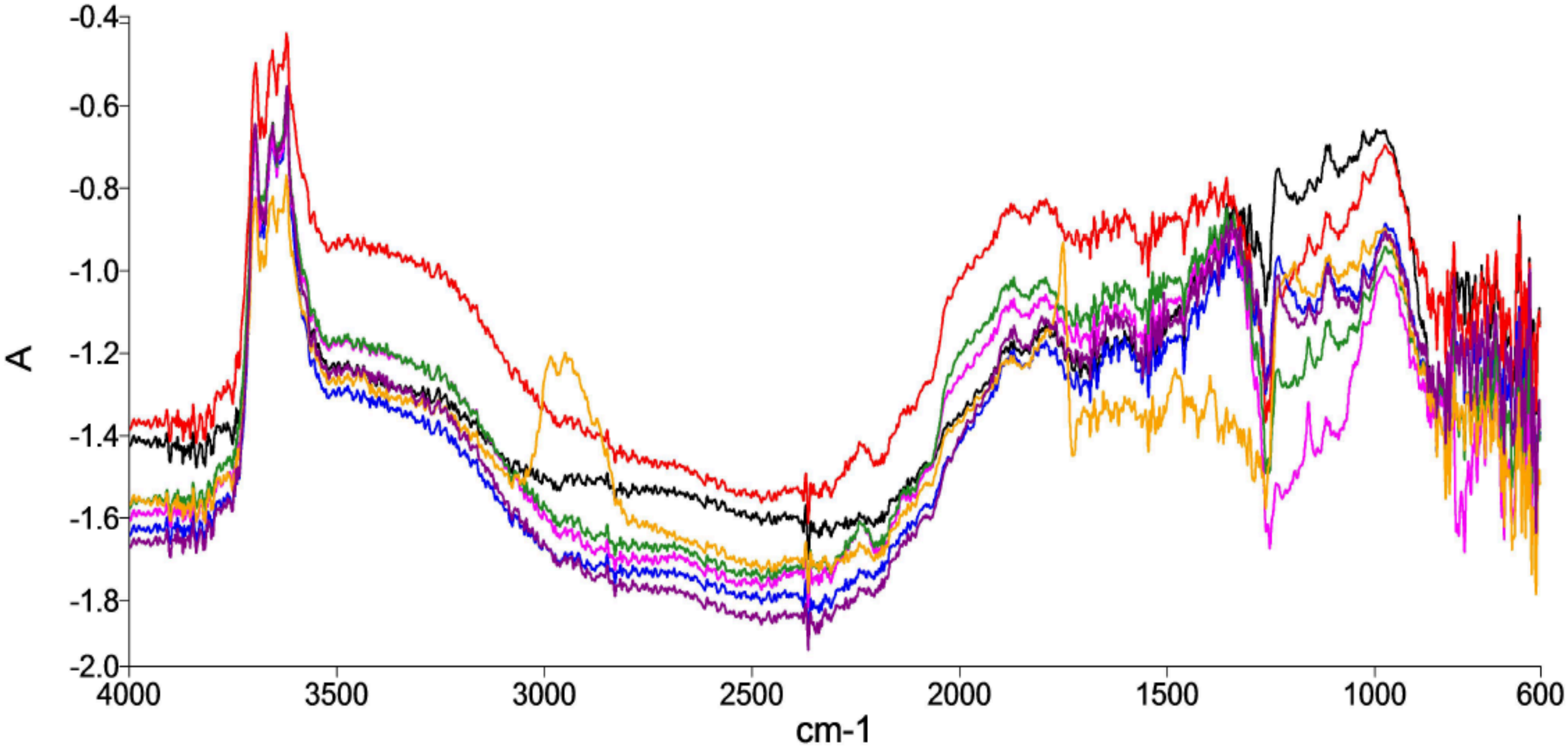
Presentation of FTIR data

Determining consolidation depth in analogue blocks: testing the analysis methodology
Analogue Sample 1, 5% Primal B60A v/v in deionised water applied via pipette to the surface of a mudbrick



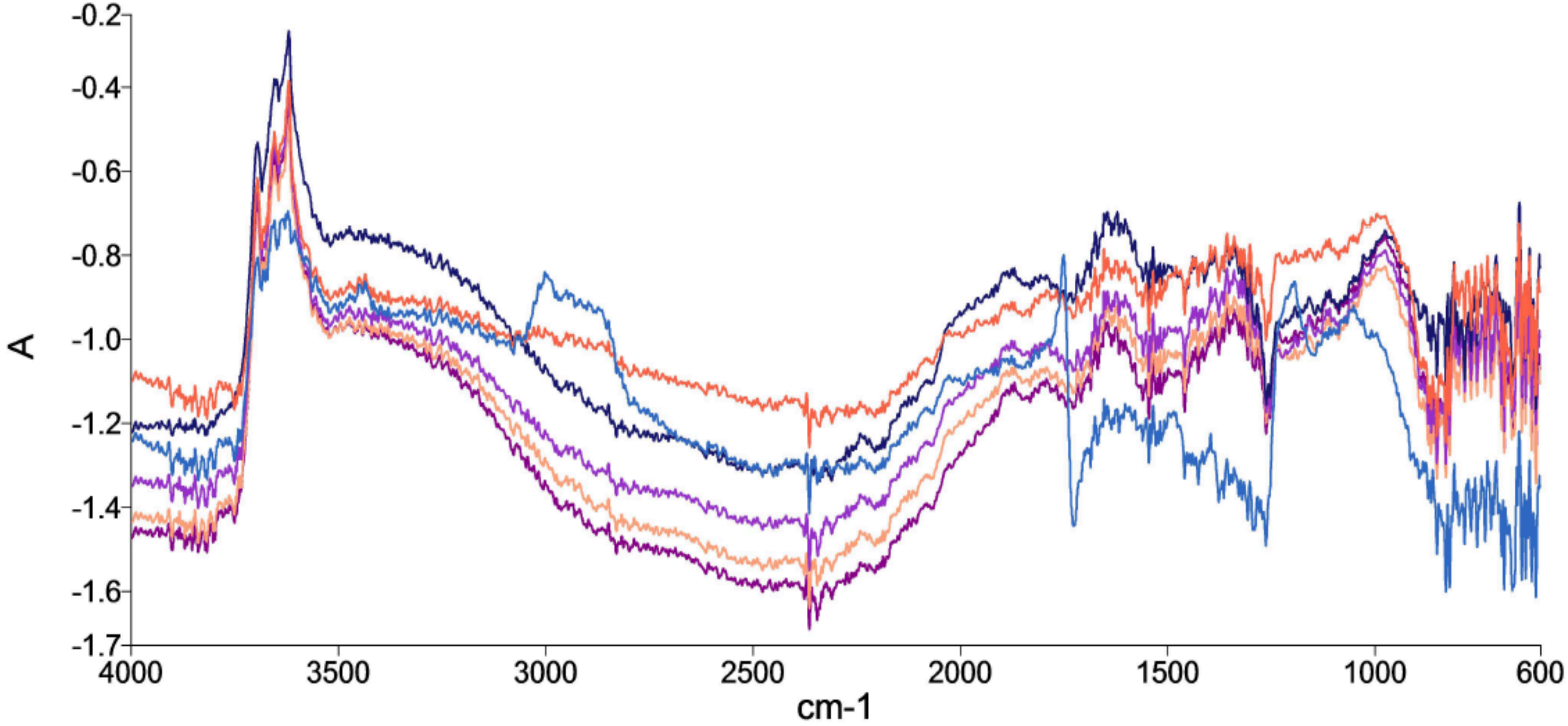
Spectra collected by FTIR Multiscope, cross-section analysis. One scan per location, in descending order: surface (black), break edge (red), 1mm (pink), 5mm (green)

Determining consolidation depth in analogue blocks: testing the analysis methodology
Analogue Sample 2, 5% Primal B60A v/v in deionised water applied via pipette to the surface of a mudbrick



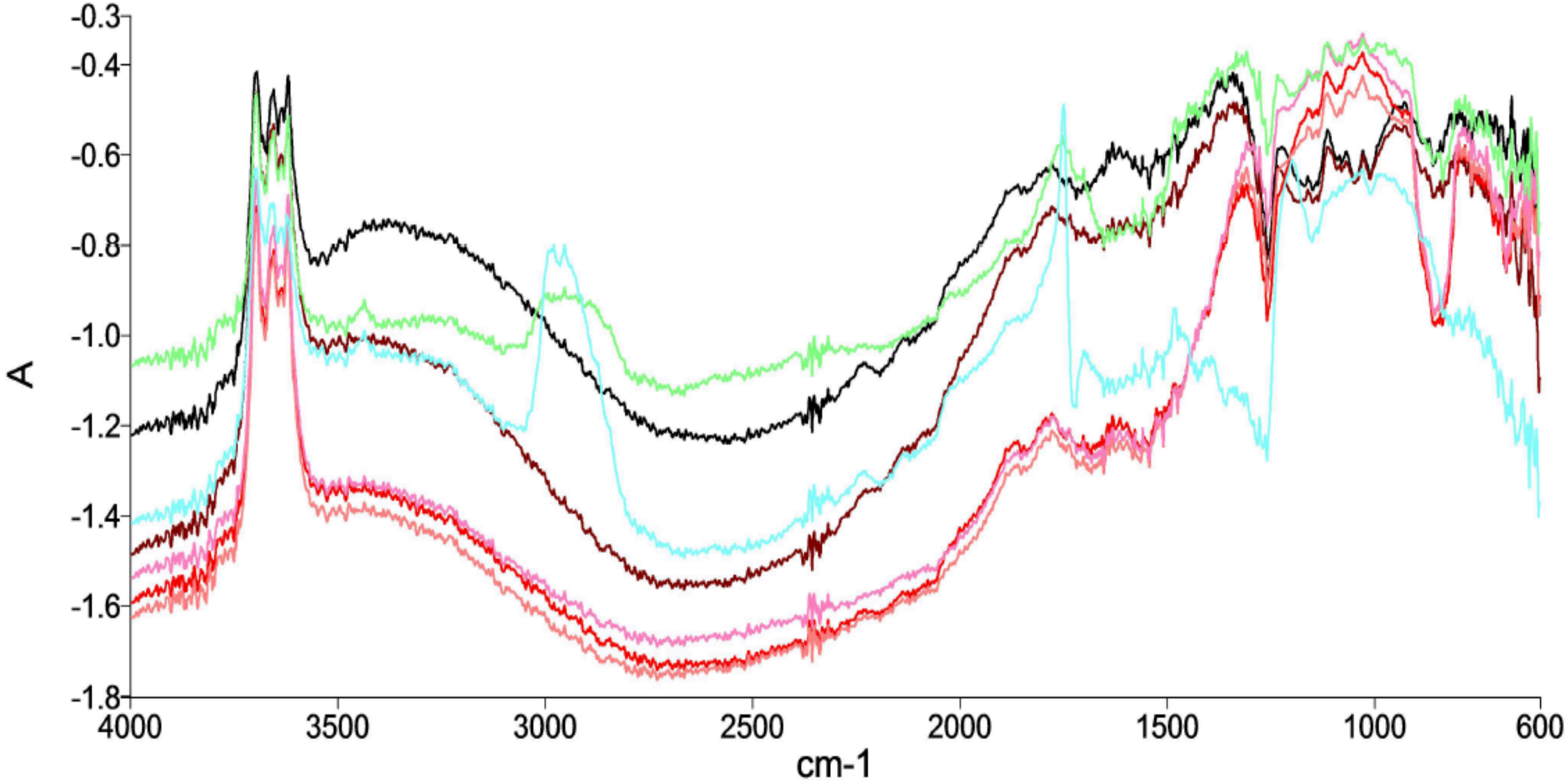
Spectra collected by FTIR Multiscope, cross-section analysis. One scan per location, in descending order: surface (yellow), break edge (black), 1mm (red), 2mm (blue), 3mm (pink), 4mm (green), 5mm (purple)

Determining consolidation depth in analogue blocks: testing the analysis methodology
Analogue Sample 3, 5% Primal B60A v/v in deionised water applied via pipette to the surface of a mudbrick



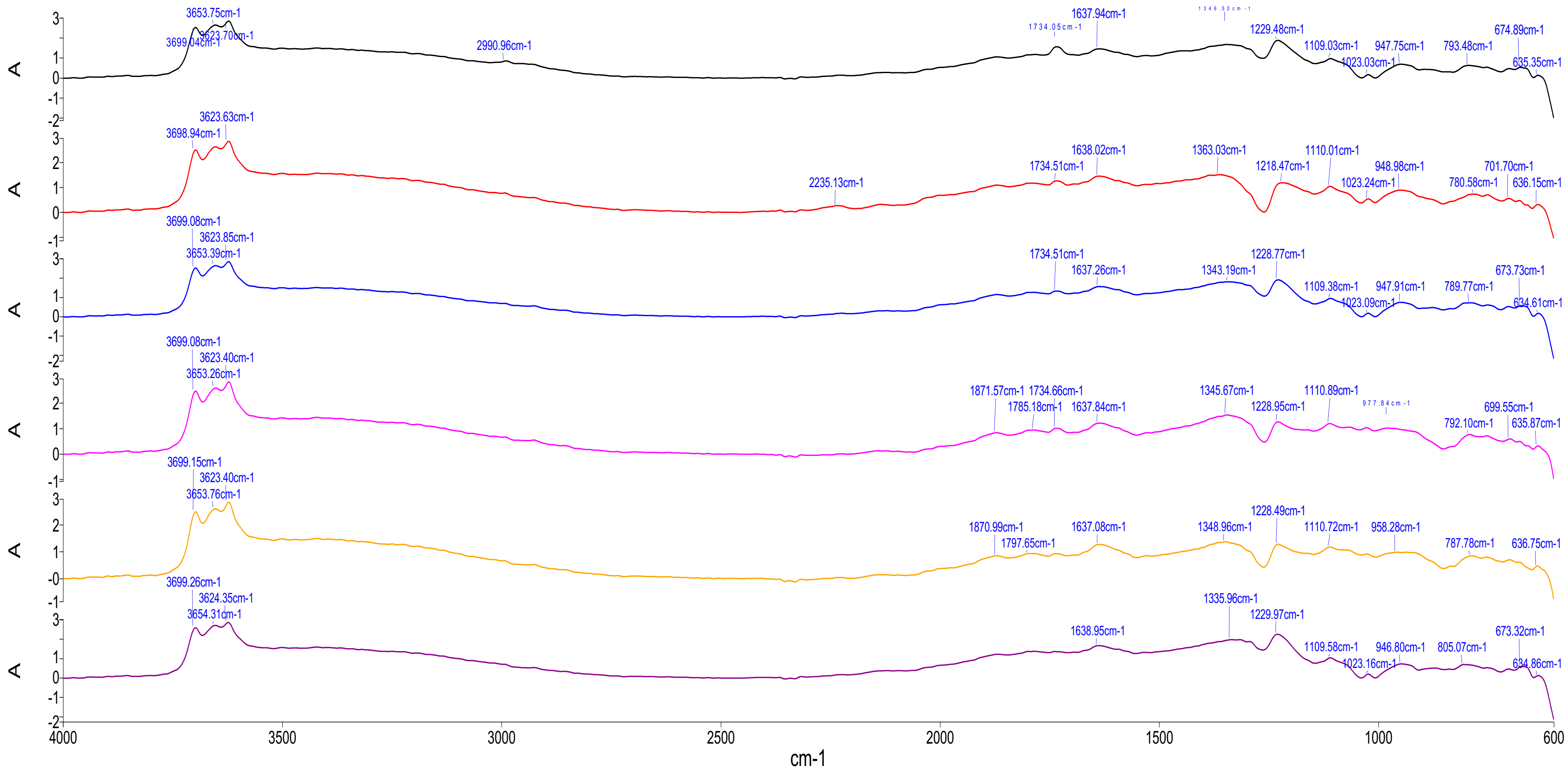
Spectra collected by FTIR Multiscope, cross-section analysis. One scan per location, in descending order: surface (light blue), break edge (orange), 1mm (navy), 2mm (purple), 3mm (yellow), 4mm (burgundy)

Determining consolidation depth in analogue blocks: testing the analysis methodology
Analogue Sample 4, 5% Primal B60A v/v in deionised water applied via pipette to the surface of a mudbrick



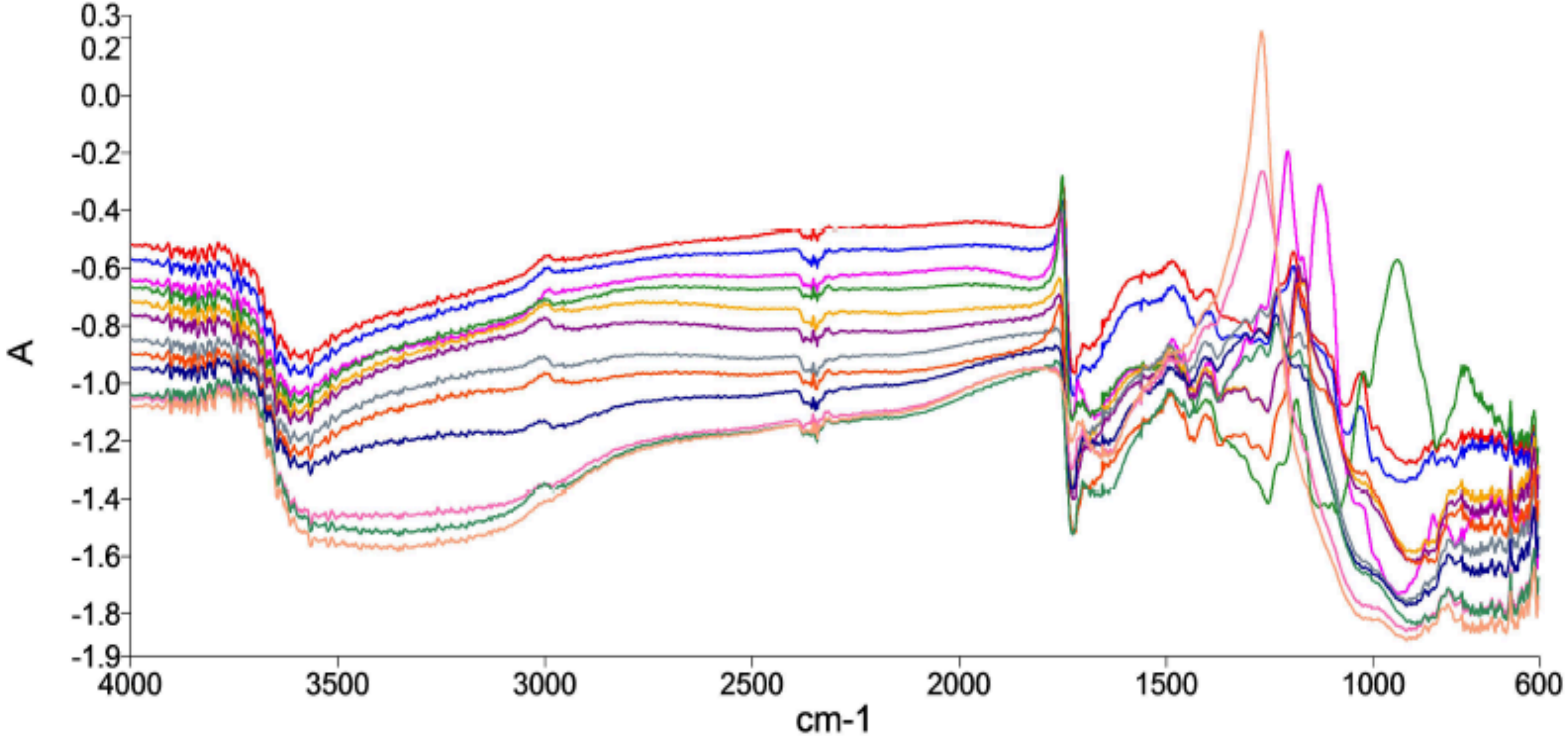
Spectra collected by FTIR Multiscope, cross-section analysis. Two scans per location, in descending order: surface (teal and green), break edge (pink and orange), 1mm (red and brown), 5mm (black)

Concentration Limits Testing Spectra Summary



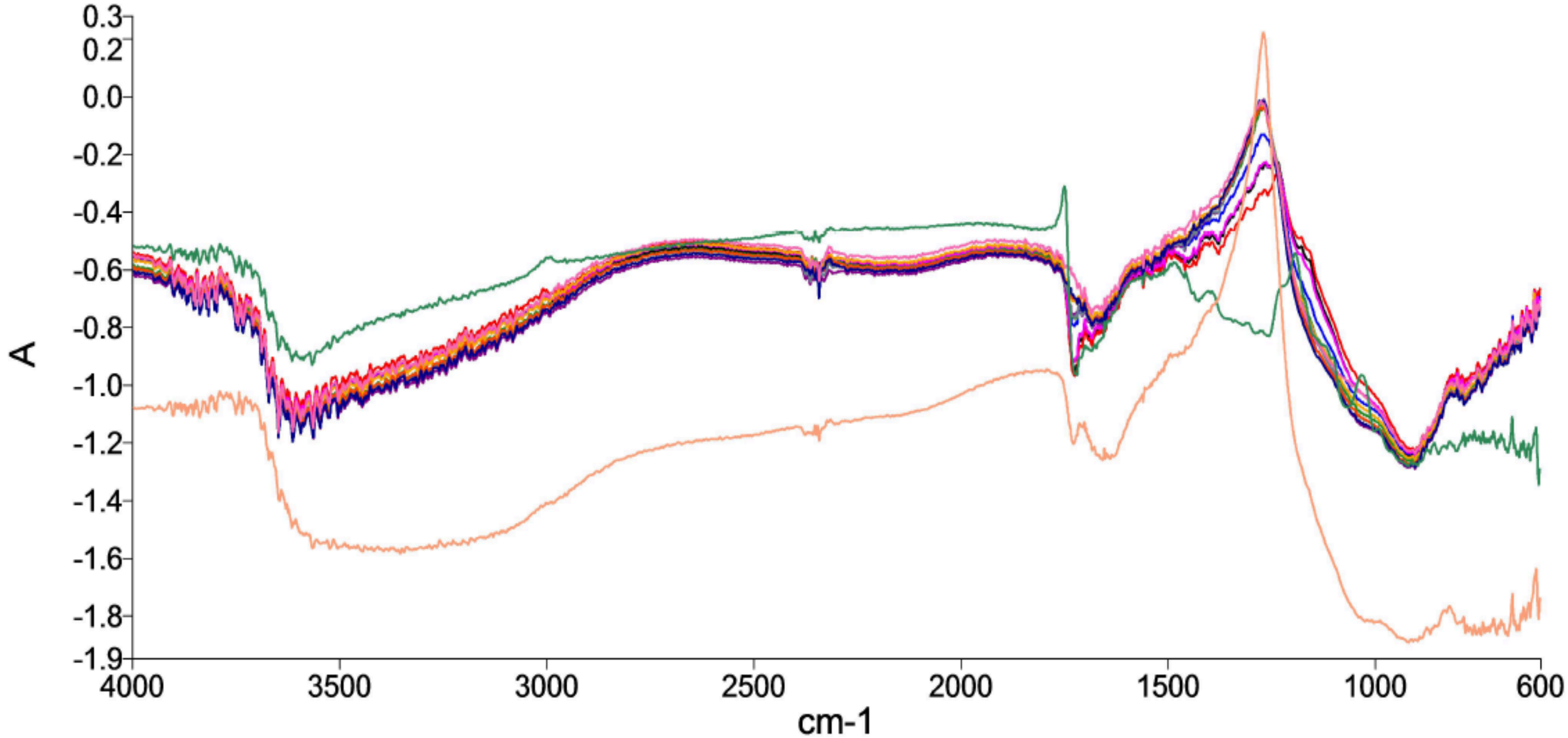
FTIR spectra from selected concentration limits calibration tests. In descending order Primal B60A mixed within an analogue mudbrick in: 5% (Black), 2.5% (red), 1.25% (blue), 0.156% (pink), 0.117% (yellow), 0.078% (purple) dilutions. Polymer peaks are circled in red.

Concentration Limits Testing Spectra



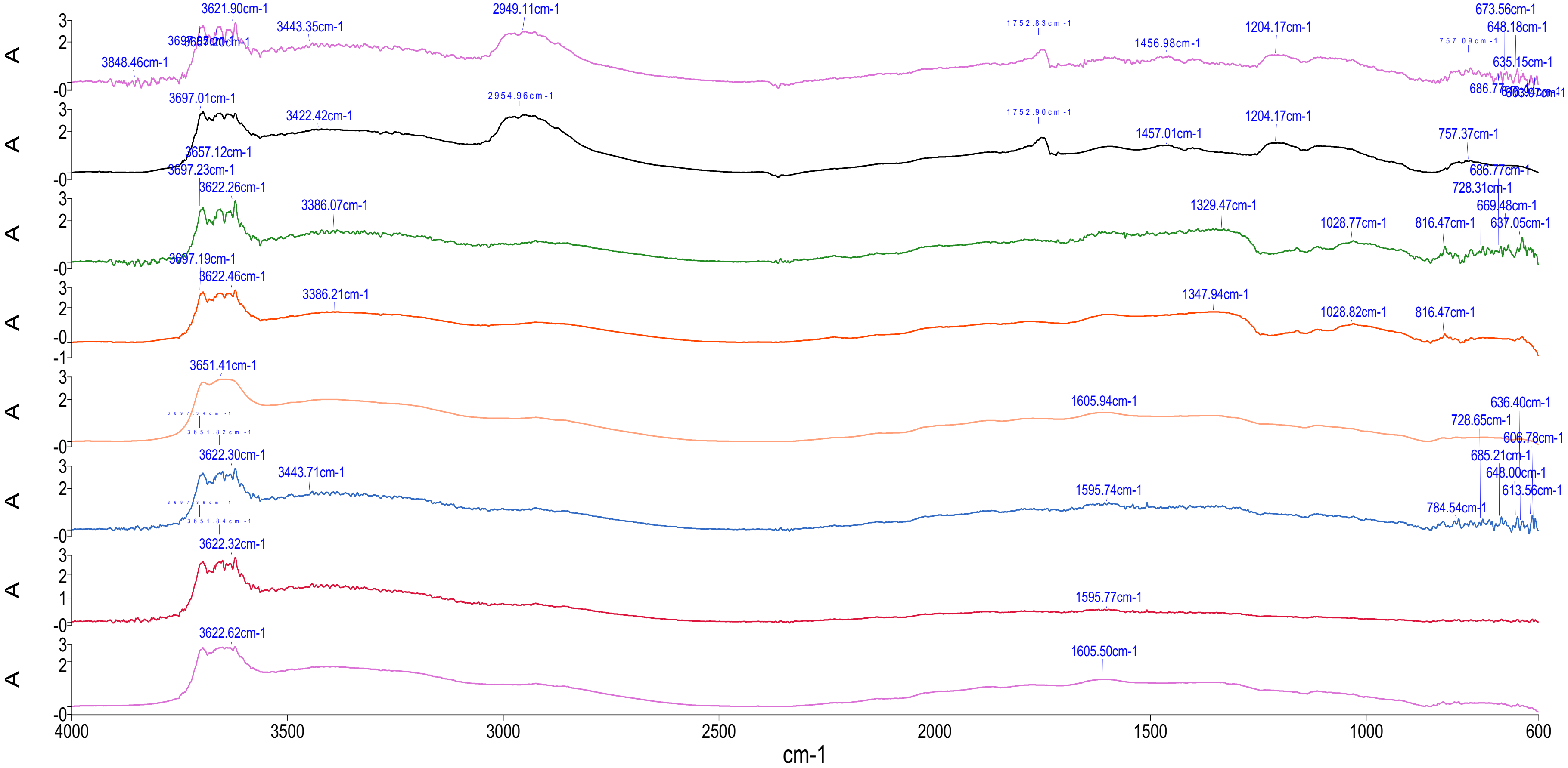
Spectra collected by FTIR Multiscope for concentration limits calibration tests Primal B60A mixed within an analogue mudbrick. 10% (red), 7.25% (blue), 5% (fuchsia), 3.75% (green), 2.5% (yellow), 1.875% (purple), 1.25% (grey), 0.938%(orange), 0.625%(navy), 0.469%(pink), 0.313% (green), 0.234%(peach)

Concentration Limits Testing Spectra



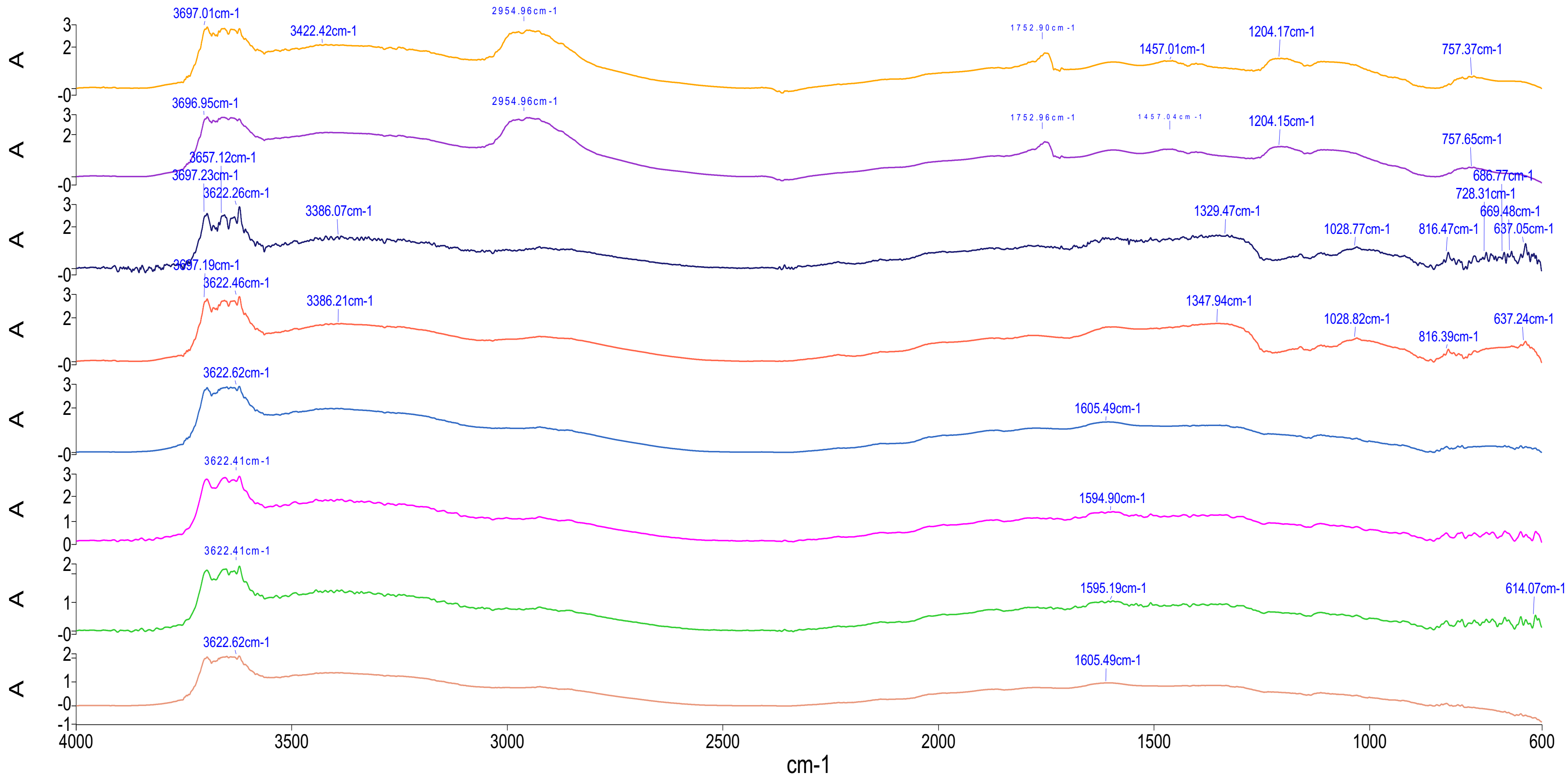
Spectra collected by FTIR Multiscope for concentration limits calibration tests Primal B60A mixed within an analogue mudbrick. 0.156% (black), 0.117% (red), 0.078% (blue), 0.058% (fuchsia), 0.039% (green), 0.029% (yellow), 0.019% (purple), 0.015% (grey), 0.009% (orange), 0.007% (navy)

Consolidation from Solution
Primal B60A 25% v/v in deionized water



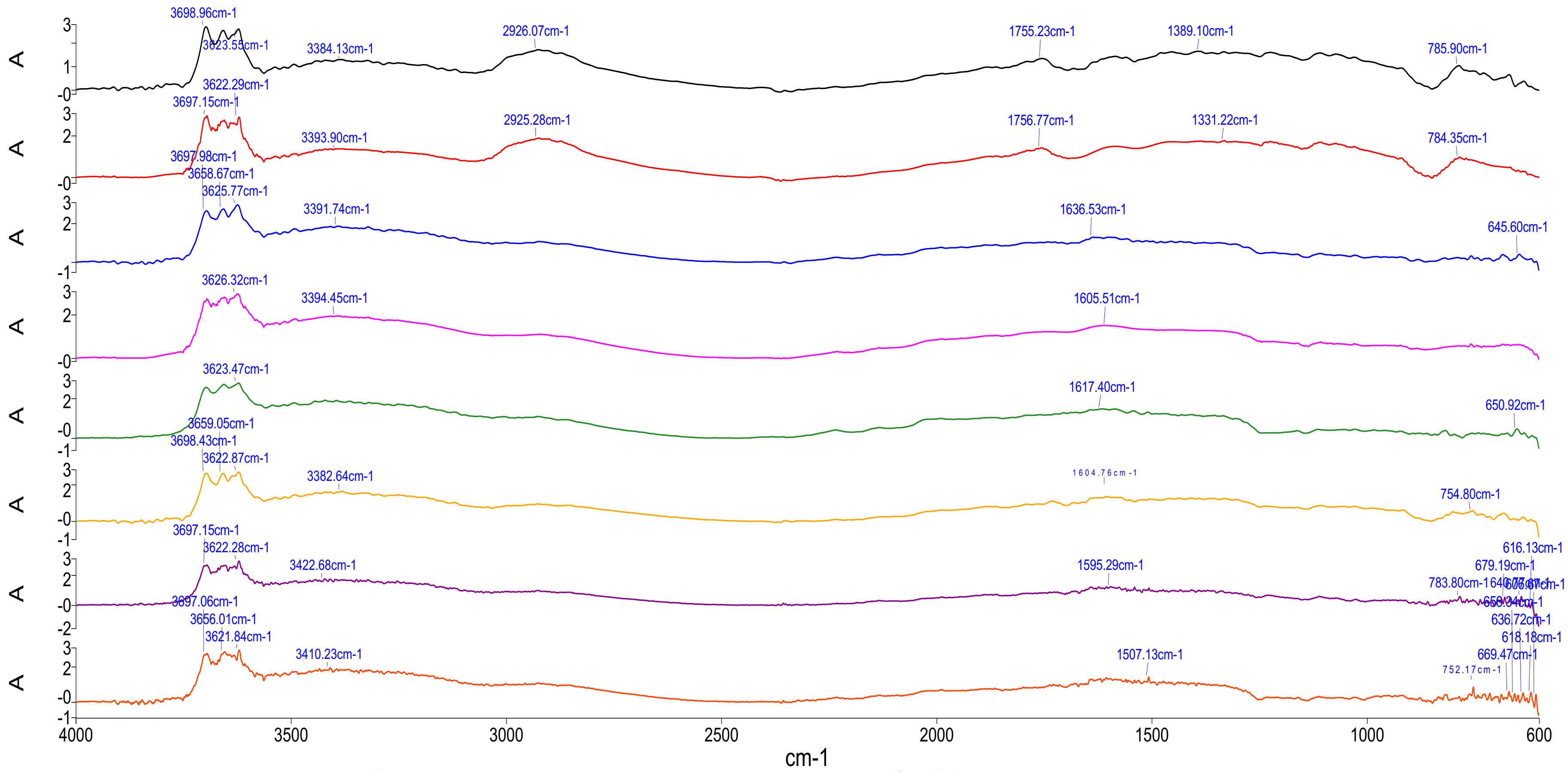
Spectra collected by FTIR Multiscope, cross-section analysis from analogue mudbrick consolidated with 5mls of 25% Primal B60A v/v in deionized water. In descending order: surface (pink and black), break-edge (green and orange), 1mm depth (peach and blue), 2mm depth (red and pink).

Primal B60A 10% v/v in deionized water



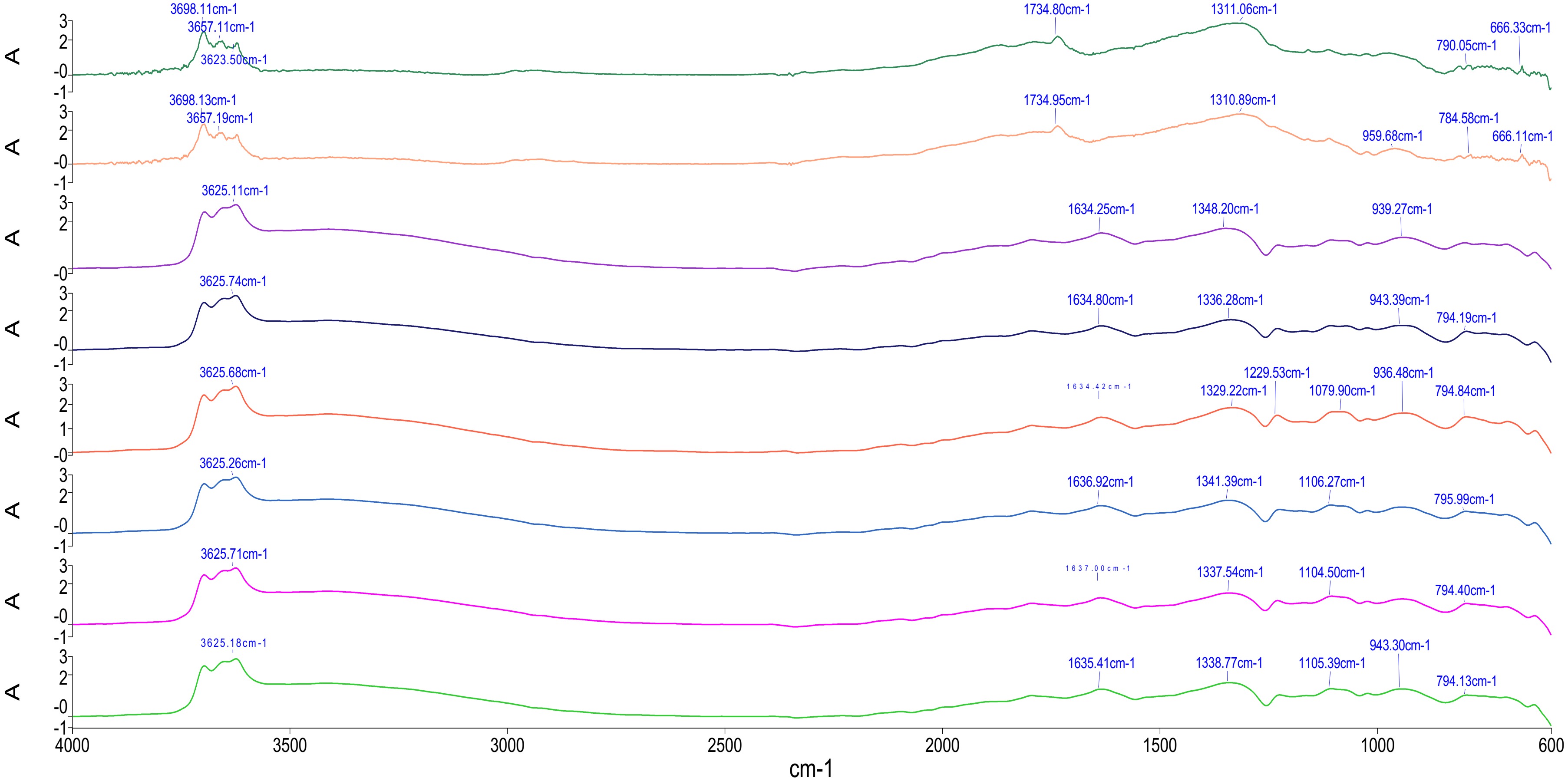
Spectra collected by FTIR Multiscope, cross-section analysis from analogue mudbrick consolidated with 5mls of 10% Primal B60A v/v in deionized water. In descending order: surface (yellow and purple), break-edge (navy and orange), 1mm depth (blue and pink), 2mm depth (green and brown).

Primal B60A 5% v/v in deionized water



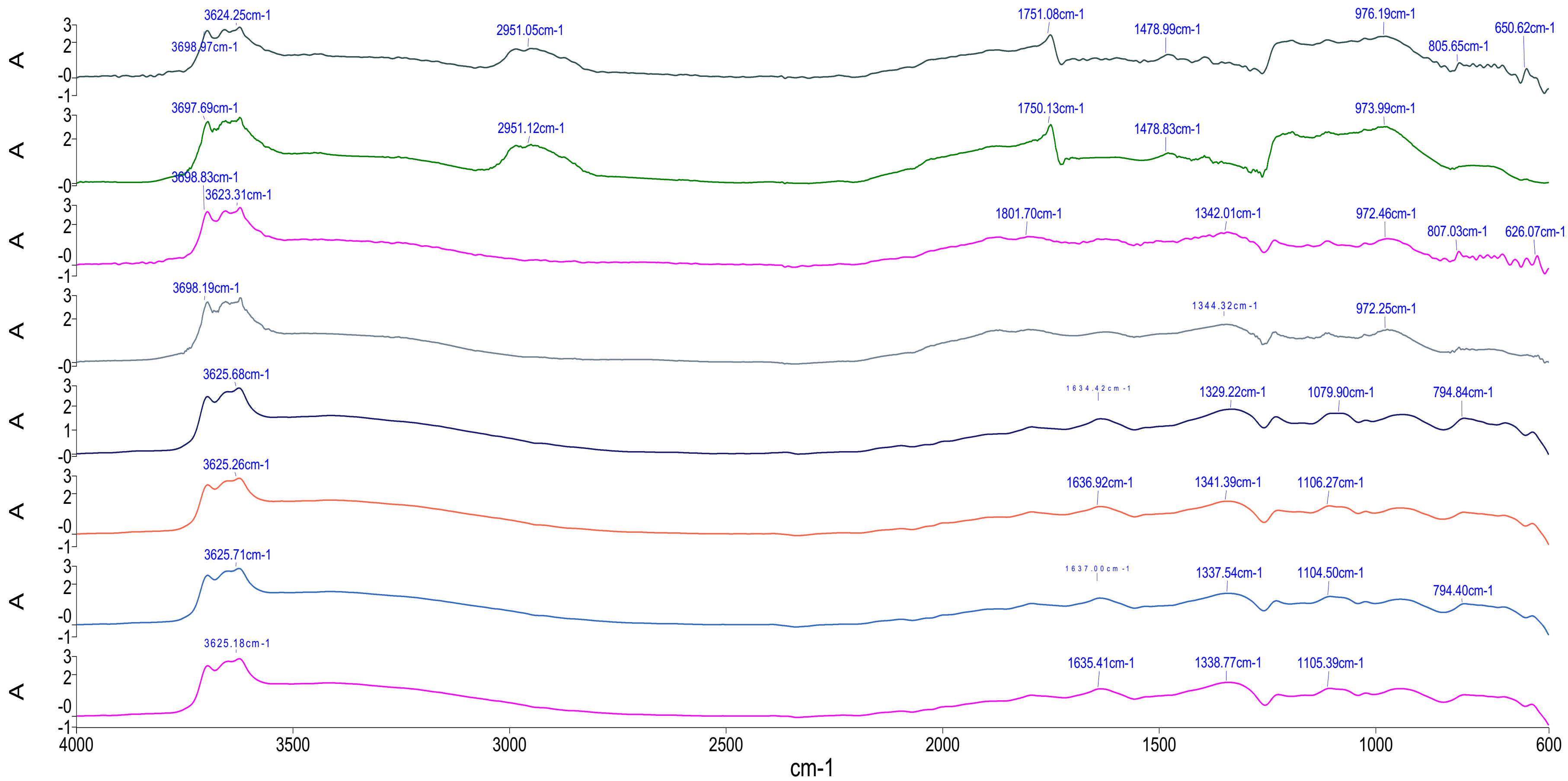
Spectra collected by FTIR Multiscope, cross-section analysis from analogue mudbrick consolidated with 5mls of 5% Primal B60A v/v in deionized water. In descending order: surface (black and red), break-edge (blue and pink), 1mm depth (green and yellow), 2mm depth (purple and orange).

Dispersion of non-aqueous systems and other commonly applied polymers
5% Primal AC-33 v/v in deionized water



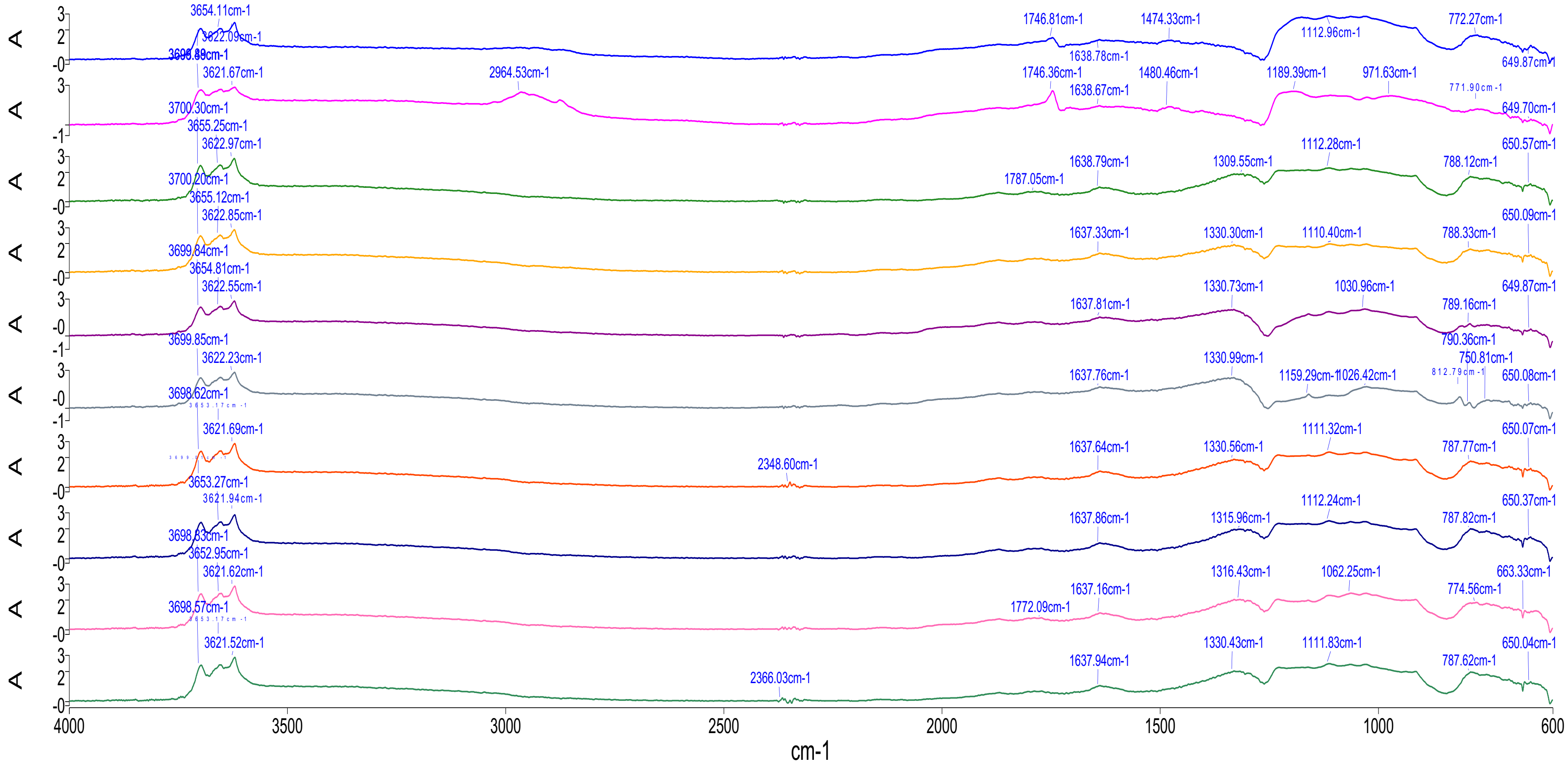
Spectra collected by FTIR Multiscope, cross-section analysis. 5% Primal AC-33 5% v/v in deionised water. Two scans per location, in descending order: surface (green and orange); break edge (purple and navy); 1mm depth (orange and blue); 5mm depth (pink and lime).

Acrysol WS-24 20% v/v in deionized water



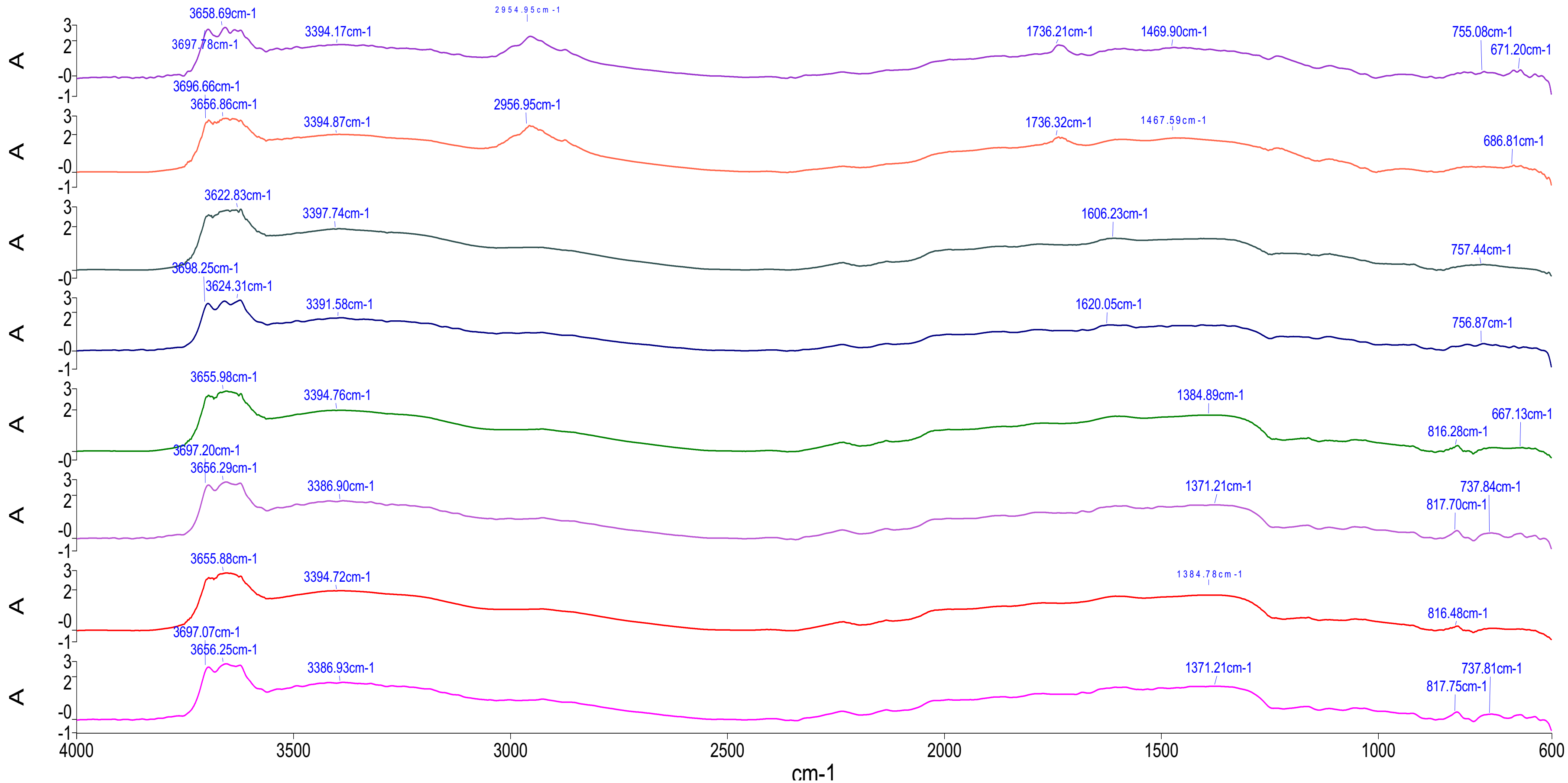
Spectra collected by FTIR Multiscope, cross-section analysis. 20% Acrysol WS-24 v/v in deionised water. Two scans per location, in descending order: surface (grey and green); break edge (pink and grey); 1mm depth (navy and orange); 5mm depth (blue and pink).

10% Acrysol WS-24



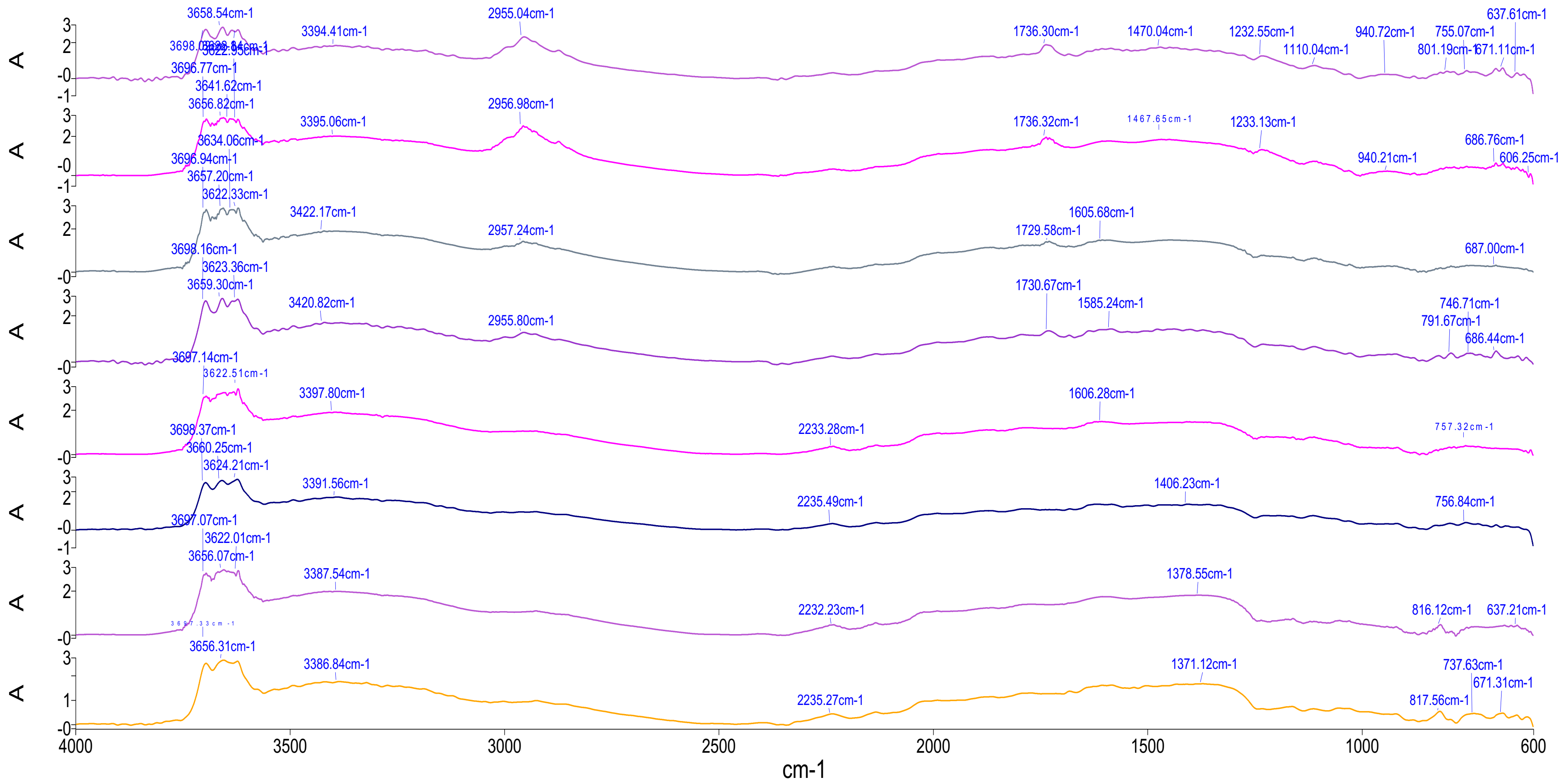
Spectra collected by FTIR Multiscope, cross-section analysis. 10% Acrysol WS-24 v/v in deionised water. Two scans per location, in descending order: surface (blue and pink); break edge (green and yellow); 1mm depth (purple and grey); 2mm depth (orange and navy); 5mm depth (pink and green).

Paraloid B-48N 10% w/v in acetone



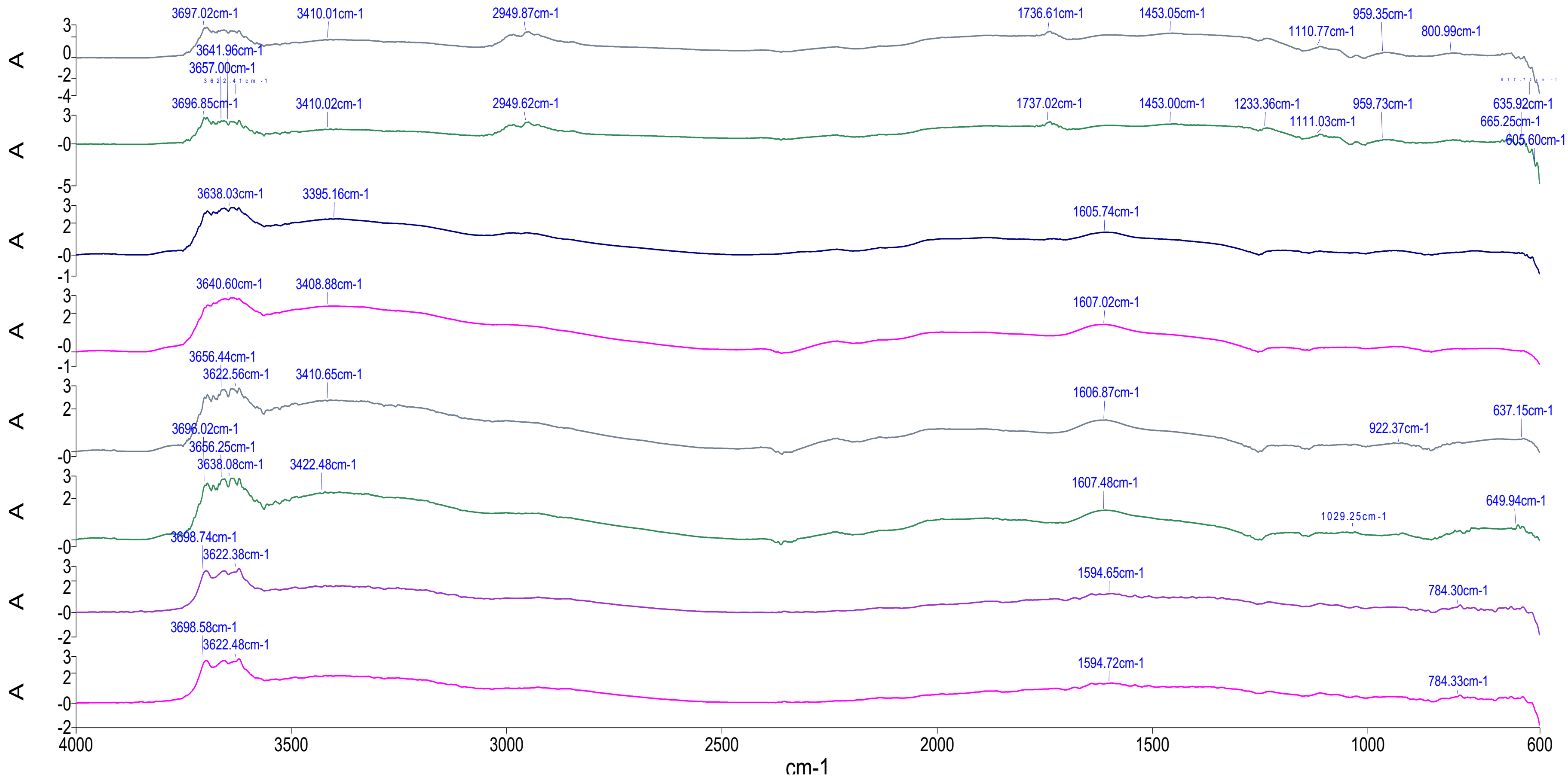
10% Paraloid B48N w/v in acetone. Two scans per location, in descending order: surface (purple and orange); break edge (grey and navy); 1mm depth (green and purple); 5mm depth (red and pink).

Paraloid B-48N 5% w/v in acetone



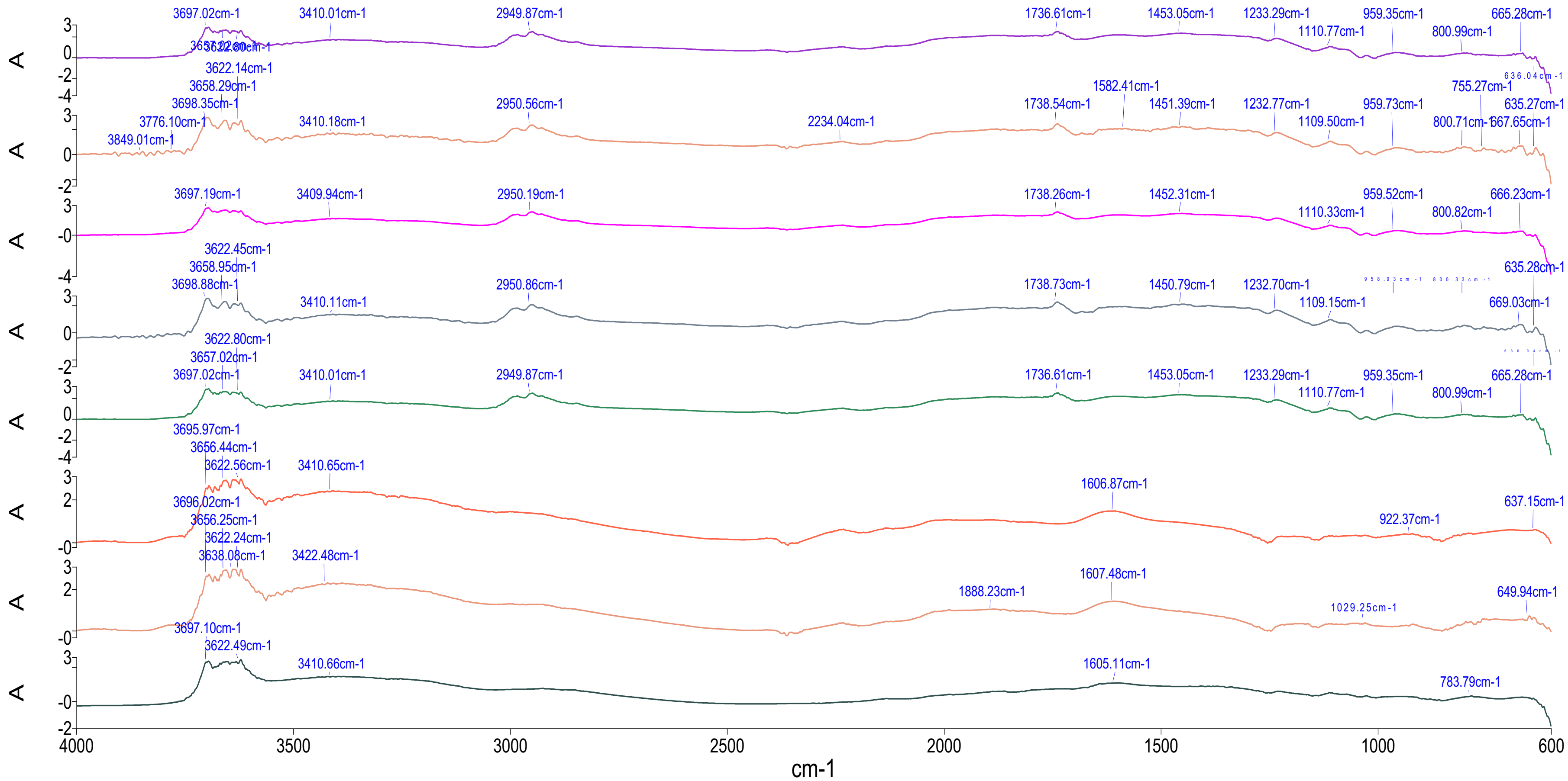
Spectra collected by FTIR Multiscope, cross-section analysis. 5% Paraloid B48N w/v in acetone. Two scans per location, in descending order: surface (purple and pink); break edge (grey and purple); 1mm depth (pink and navy); 5mm depth (purple and yellow).

Paraloid B-44 10% w/v in acetone



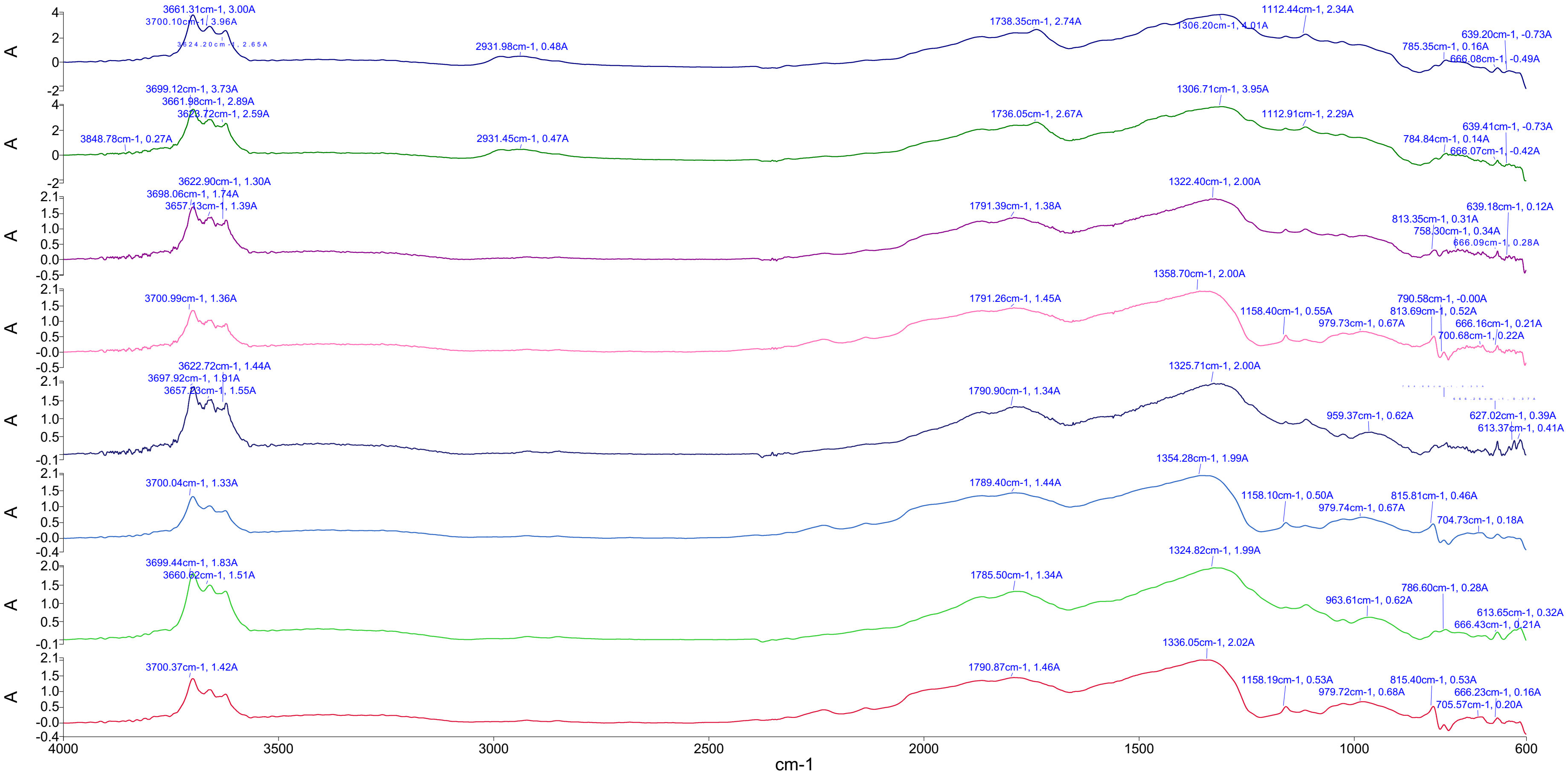
Spectra collected by FTIR Multiscope, cross-section analysis. 10% Paraloid B44 w/v in acetone. Two scans per location, in descending order: surface (grey and green); break edge (navy and pink); 1mm depth (grey and green); 5mm depth (purple and pink).

Paraloid B-44 5% w/v in acetone



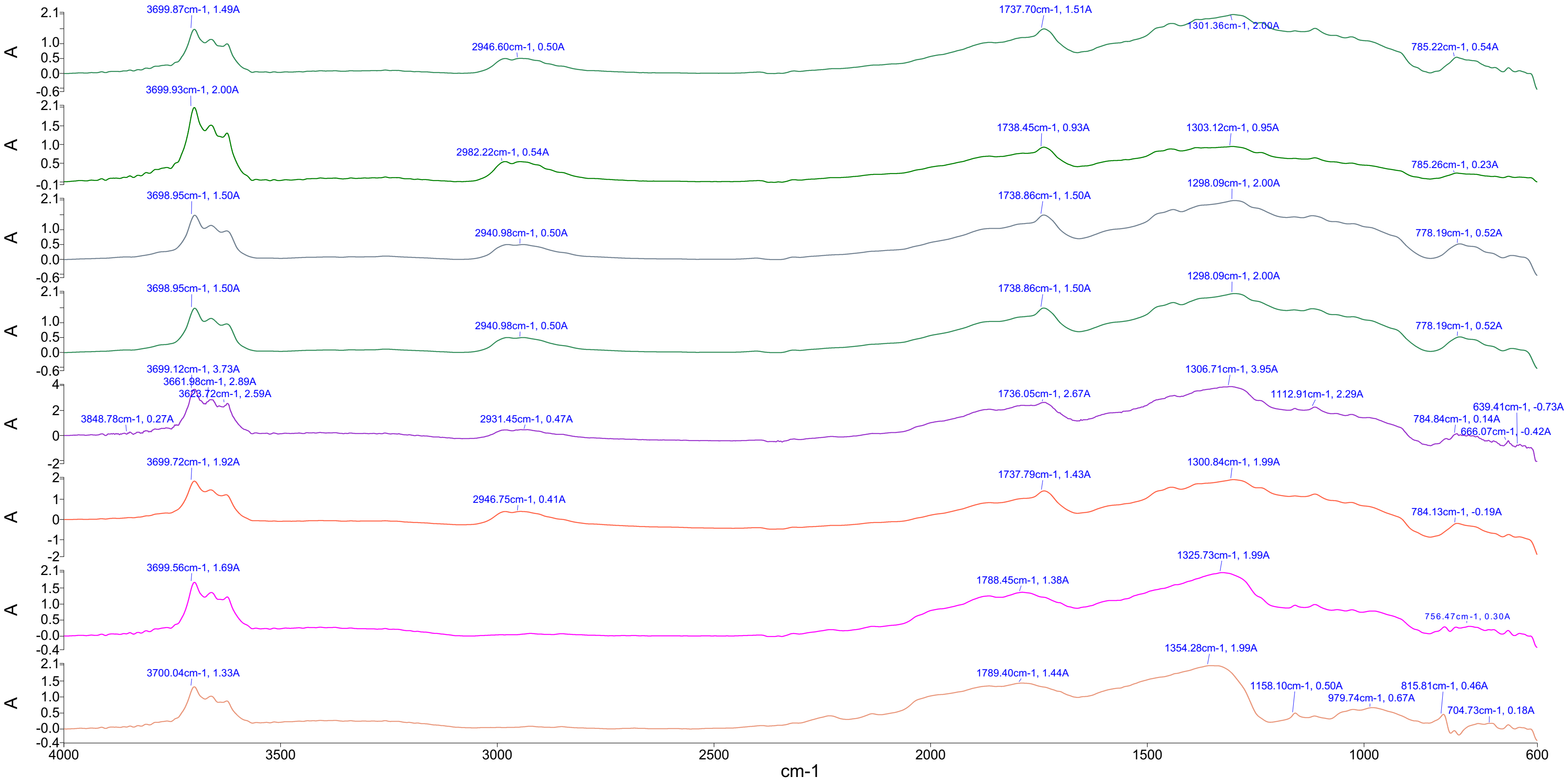
Spectra collected by FTIR Multiscope, cross-section analysis. 5% Paraloid B44 w/v in acetone. Two scans per location, in descending order: surface (purple and brown); break edge (pink and grey); 1mm depth (green and orange); 5mm depth (tan and grey).

Paraloid B72 10% w/v in acetone



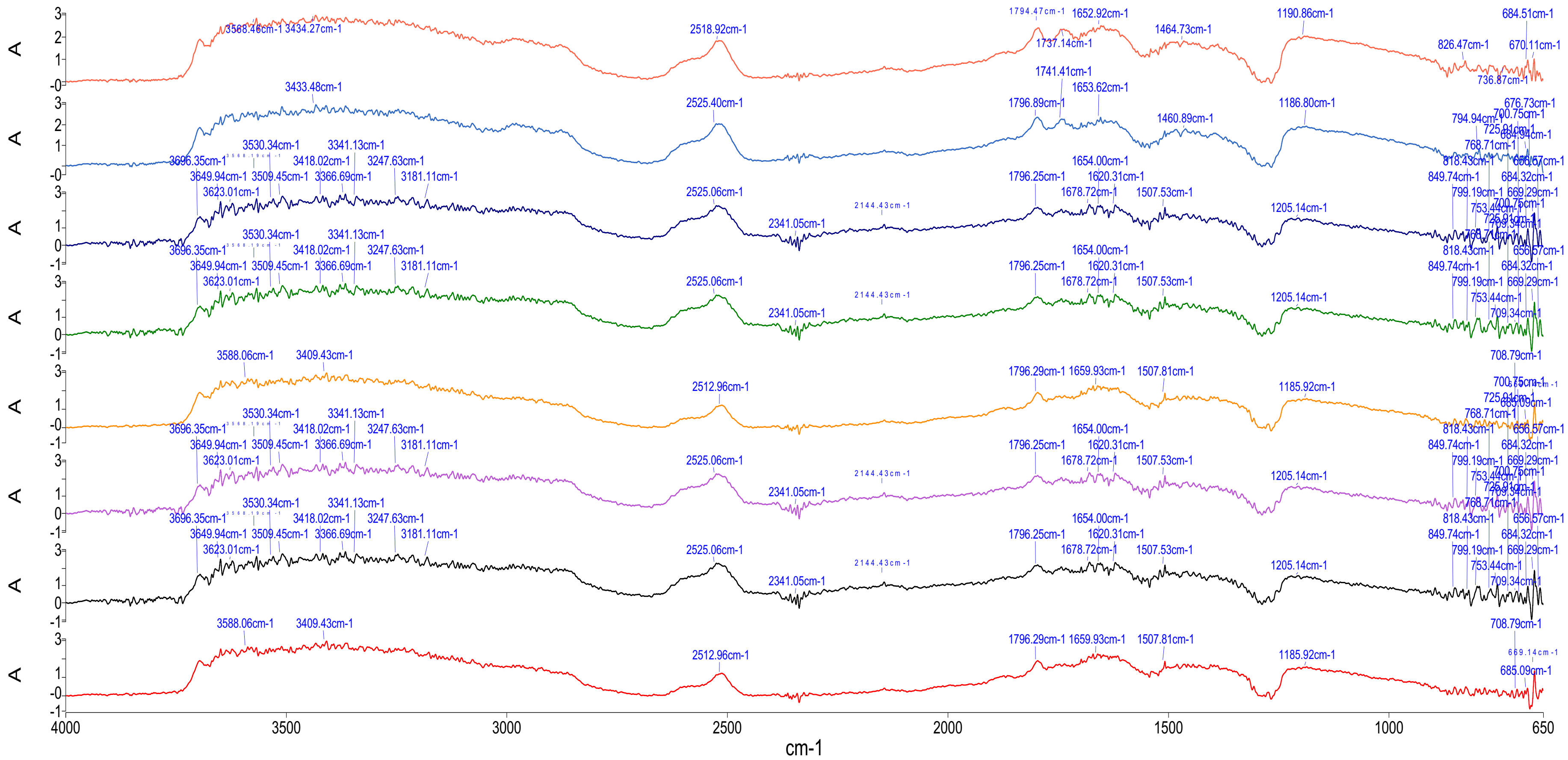
Spectra collected by FTIR Multiscope, cross-section analysis. 10% Paraloid B72 w/v in acetone. Two scans per location, in descending order: surface (navy and green); break edge (purple and pink); 1mm depth (navy and blue); 5mm depth (green and red).

Paraloid B72 5% w/v in acetone



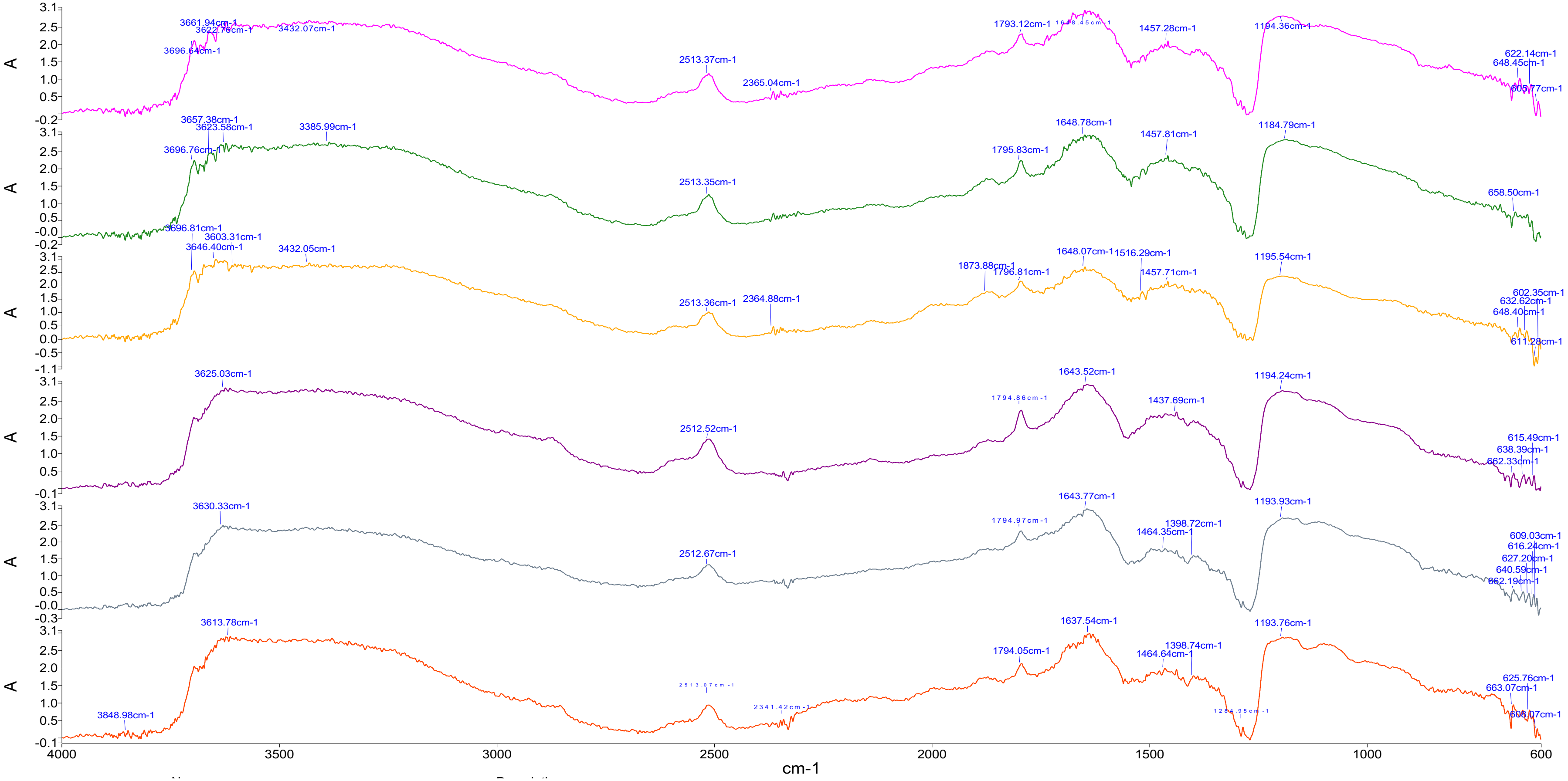
Spectra collected by FTIR Multiscope, cross-section analysis. 5% Paraloid B72 w/v in acetone. Two scans per location, in descending order: surface (teal and green); break edge (grey and green); 1mm depth (purple and orange); 5mm depth (pink and tan).

Çatalhöyük Samples
U3866_s4



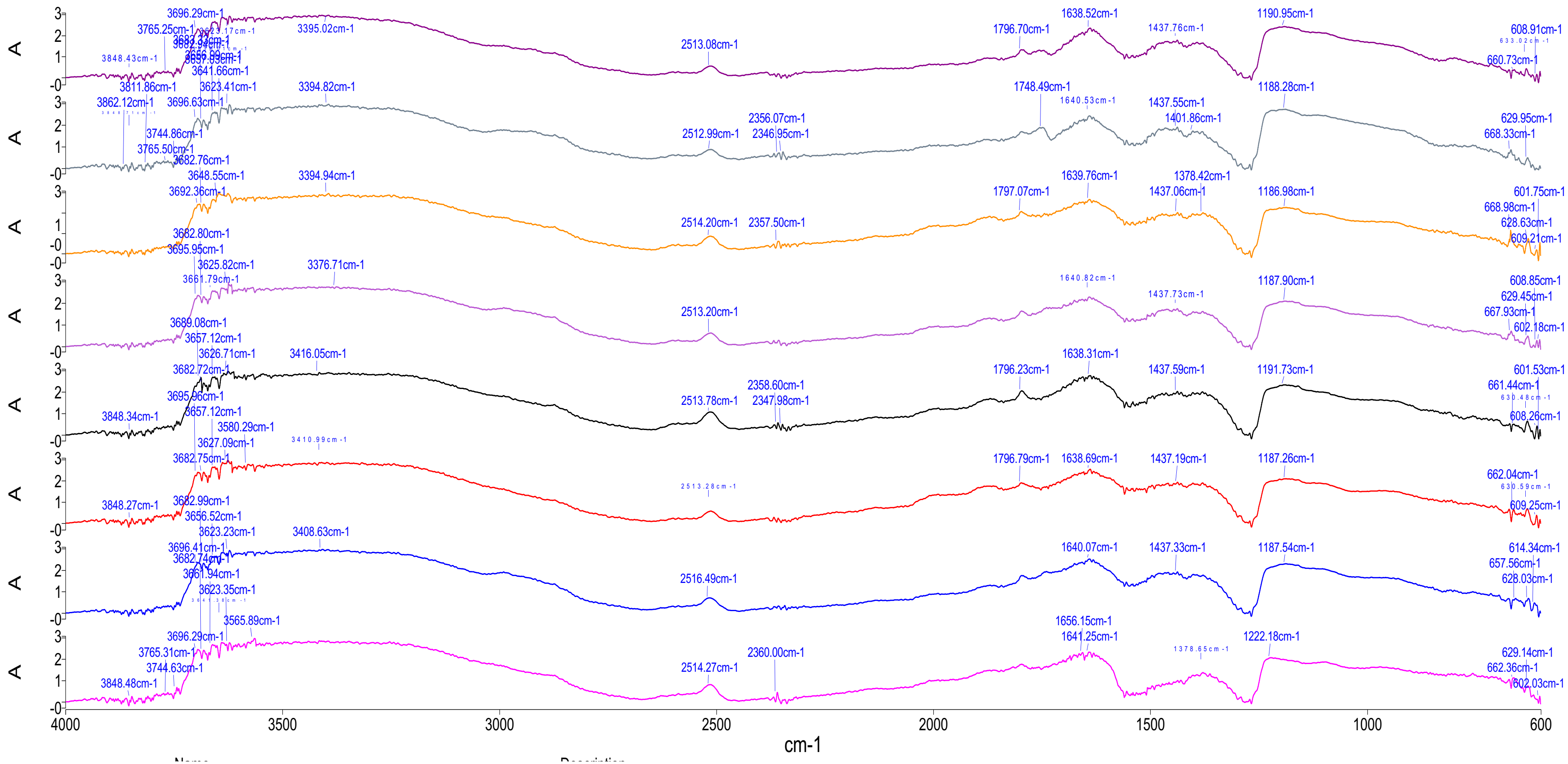
Çatalhöyük mudbrick (unit 3866, feature 230, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (orange and blue); break-edge (navy and green) 1mm depth (yellow and purple); 5mm depth (black and red).

U12321_s5



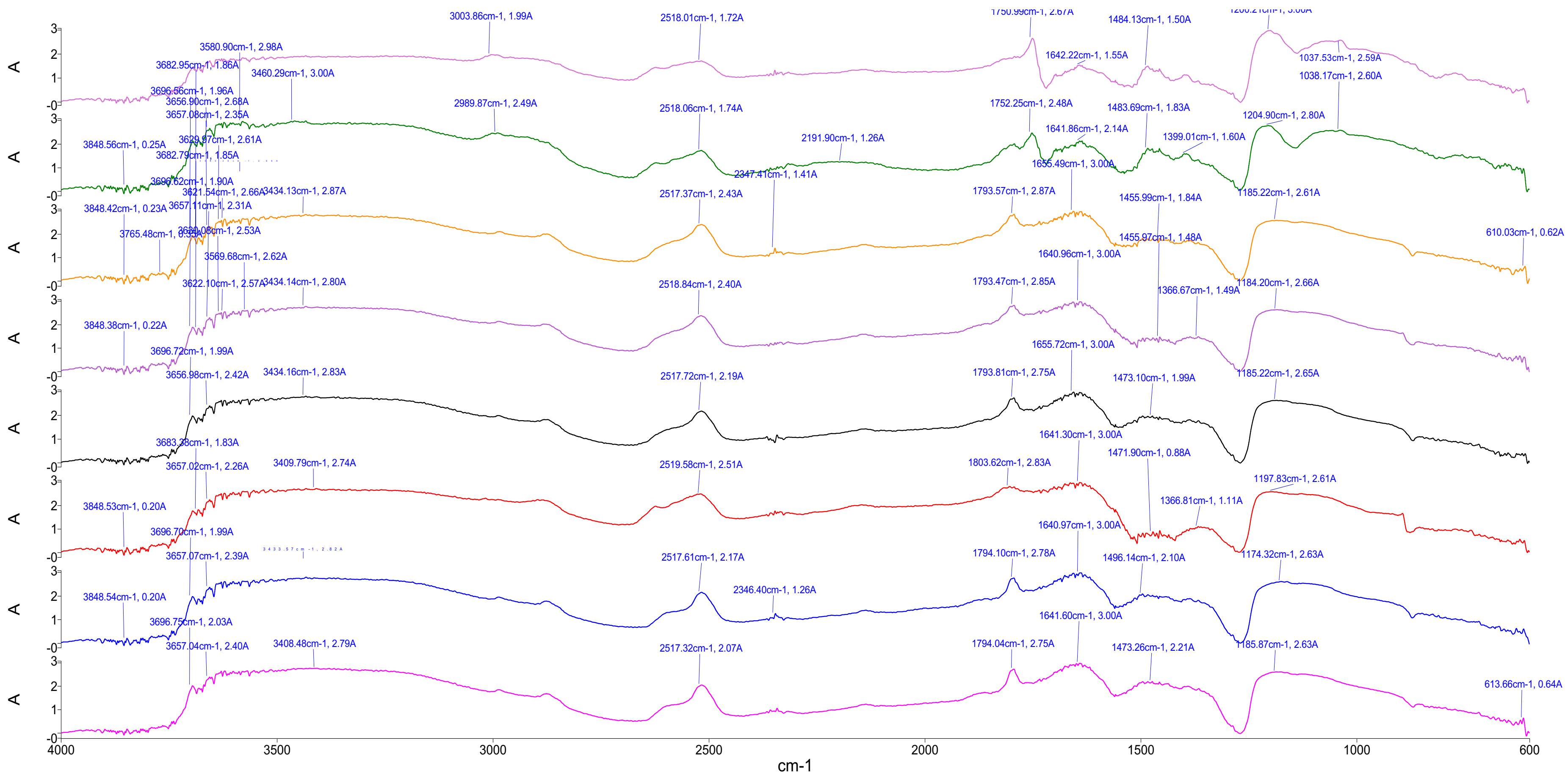
Çatalhöyük mudbrick (unit 12321, feature 1591, Building 55, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (yellow and purple) 1mm depth (grey and red)

U15838_s2



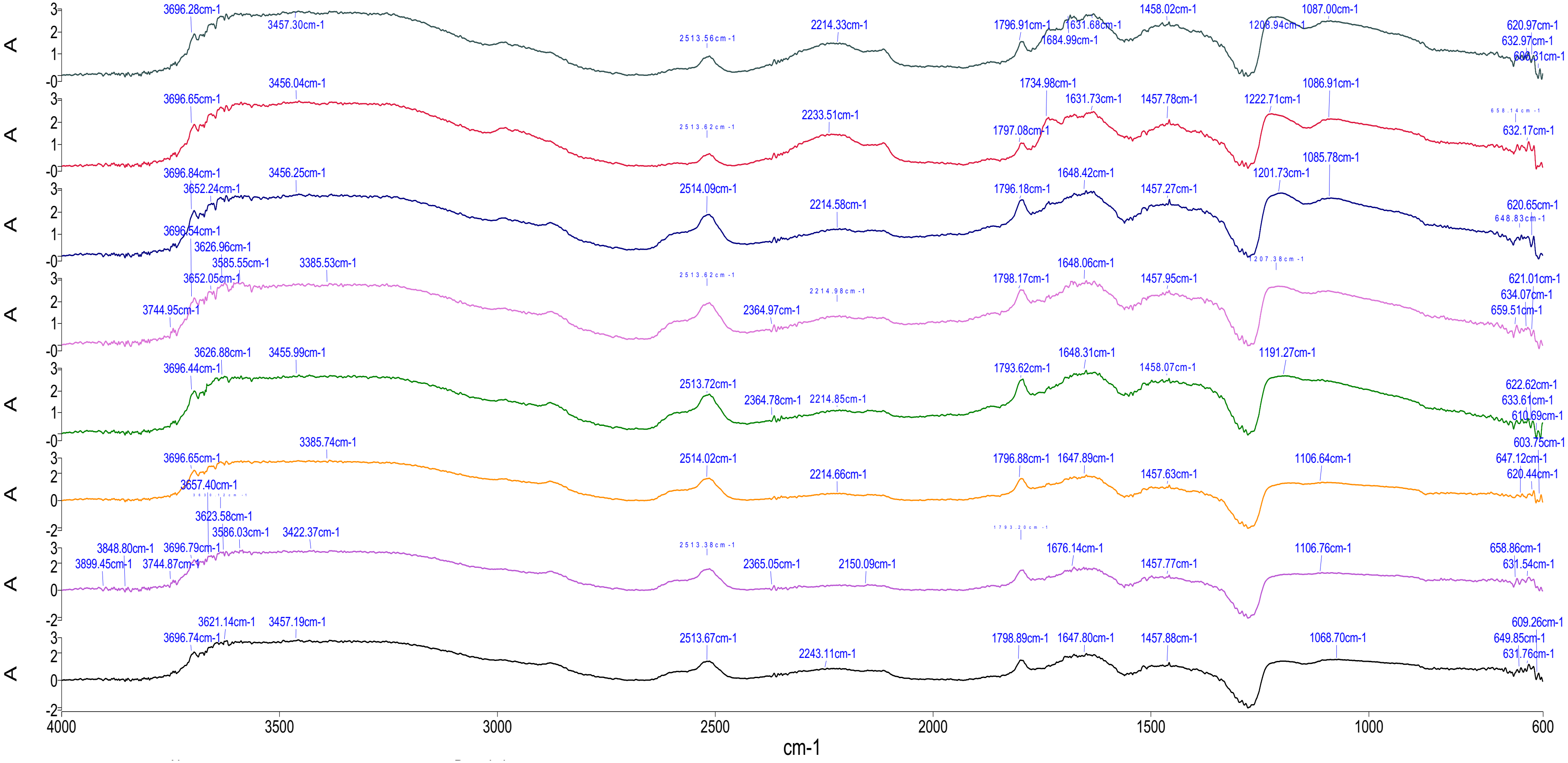
Çatalhöyük mudbrick (unit 15838, feature 6000, TP Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (burgundy and grey); break-edge (yellow and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U16368_s1



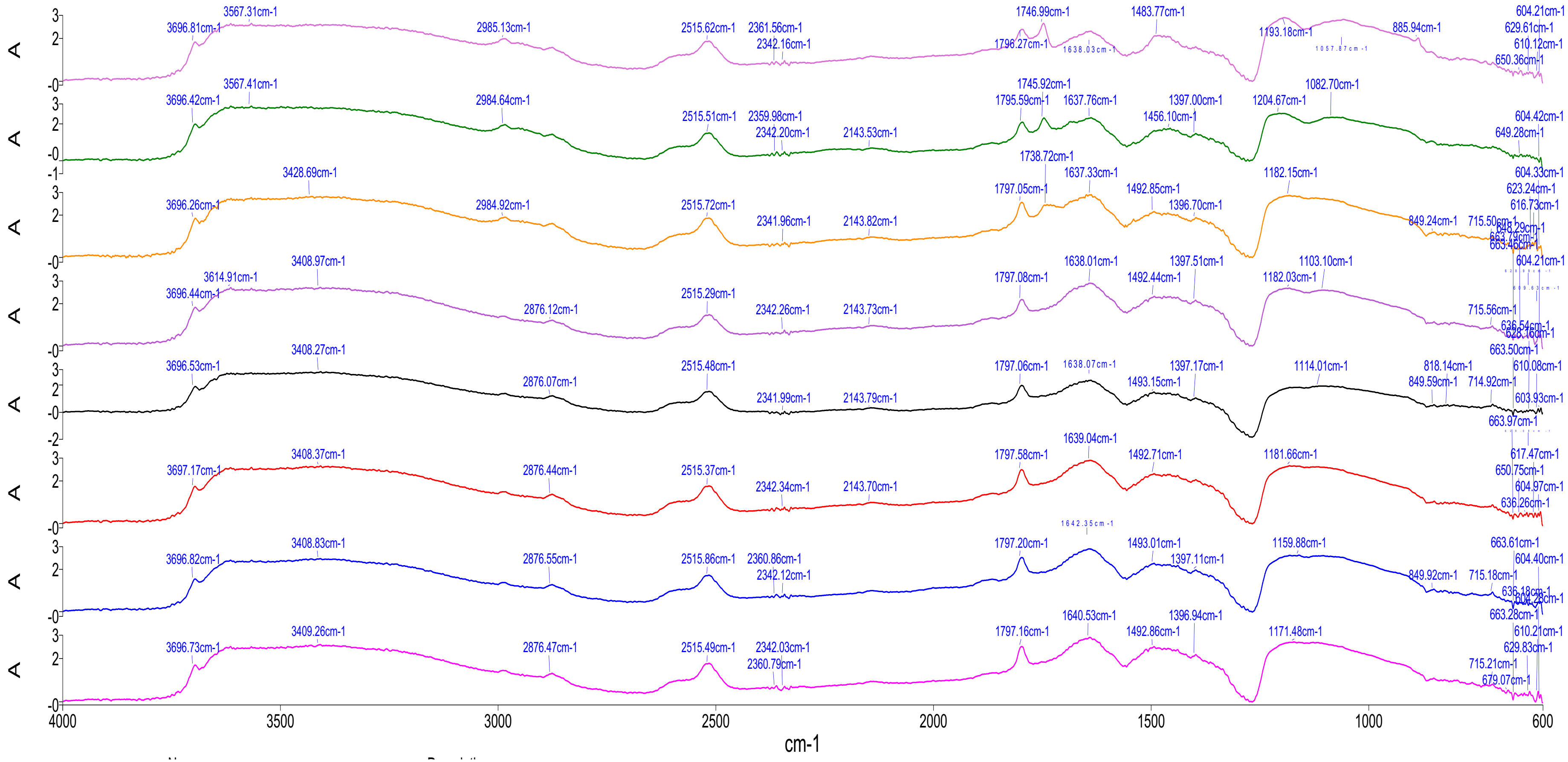
Çatalhöyük mudbrick (unit 16368, feature 1519, Building 55, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U17750_s1



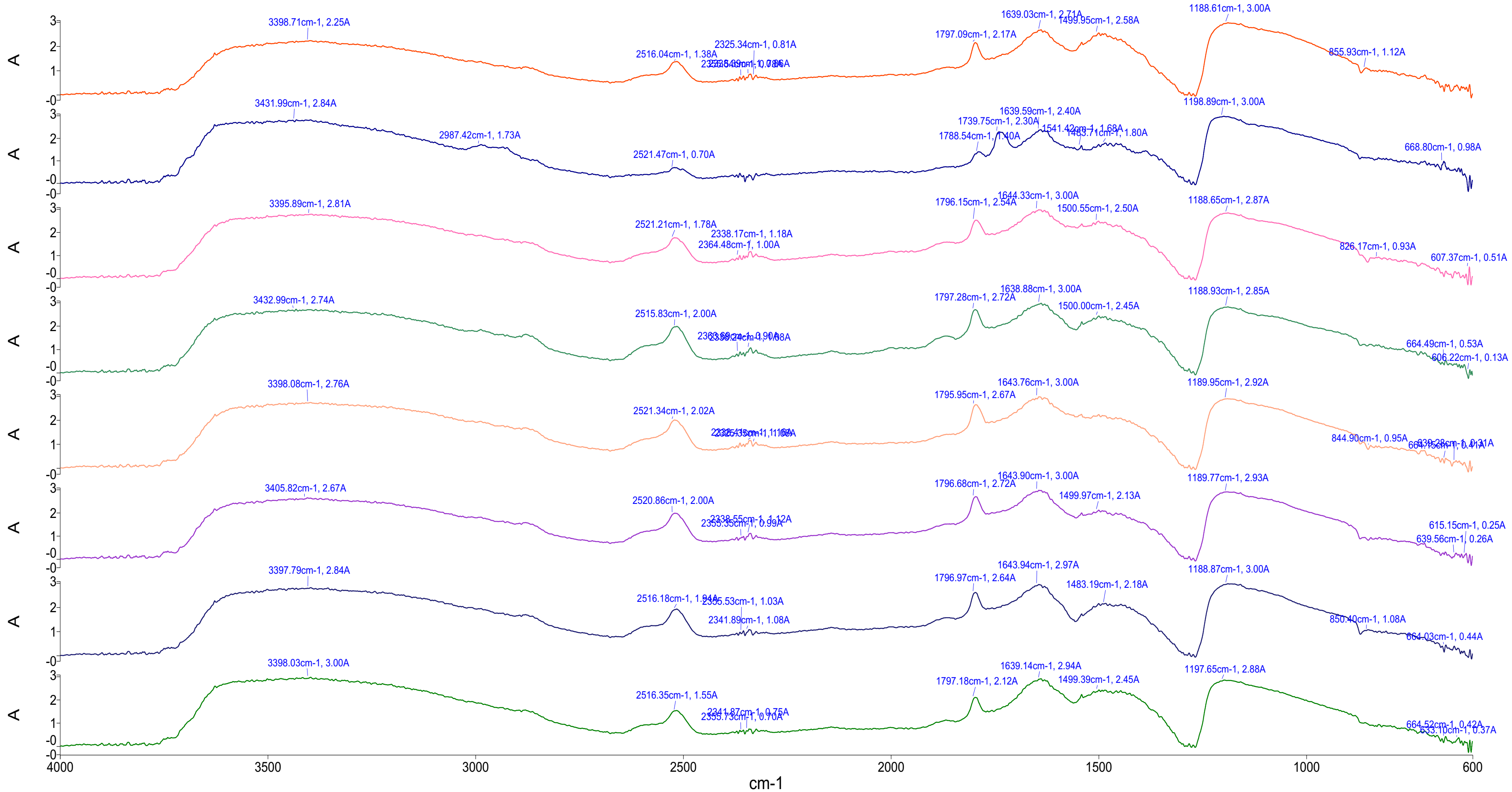
Çatalhöyük mudbrick (unit 17750, feature 1617, Building 82, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (grey and red); break-edge (blue and pink) 1mm depth (green and yellow); 5mm depth (purple and black).

U17753_s1



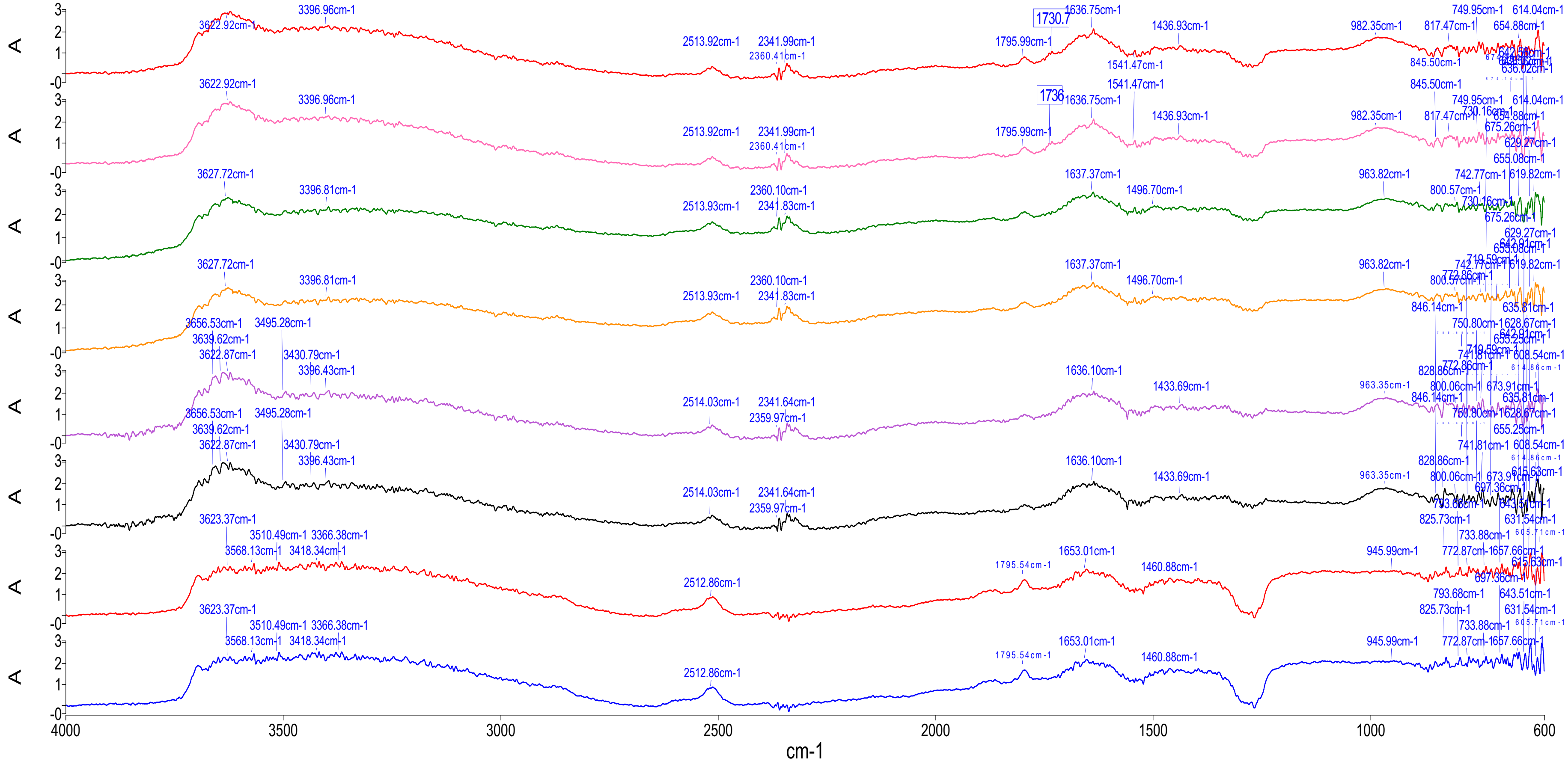
Çatalhöyük mudbrick (unit 17753, feature 1615, Building 82, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (yellow and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U18570_s1



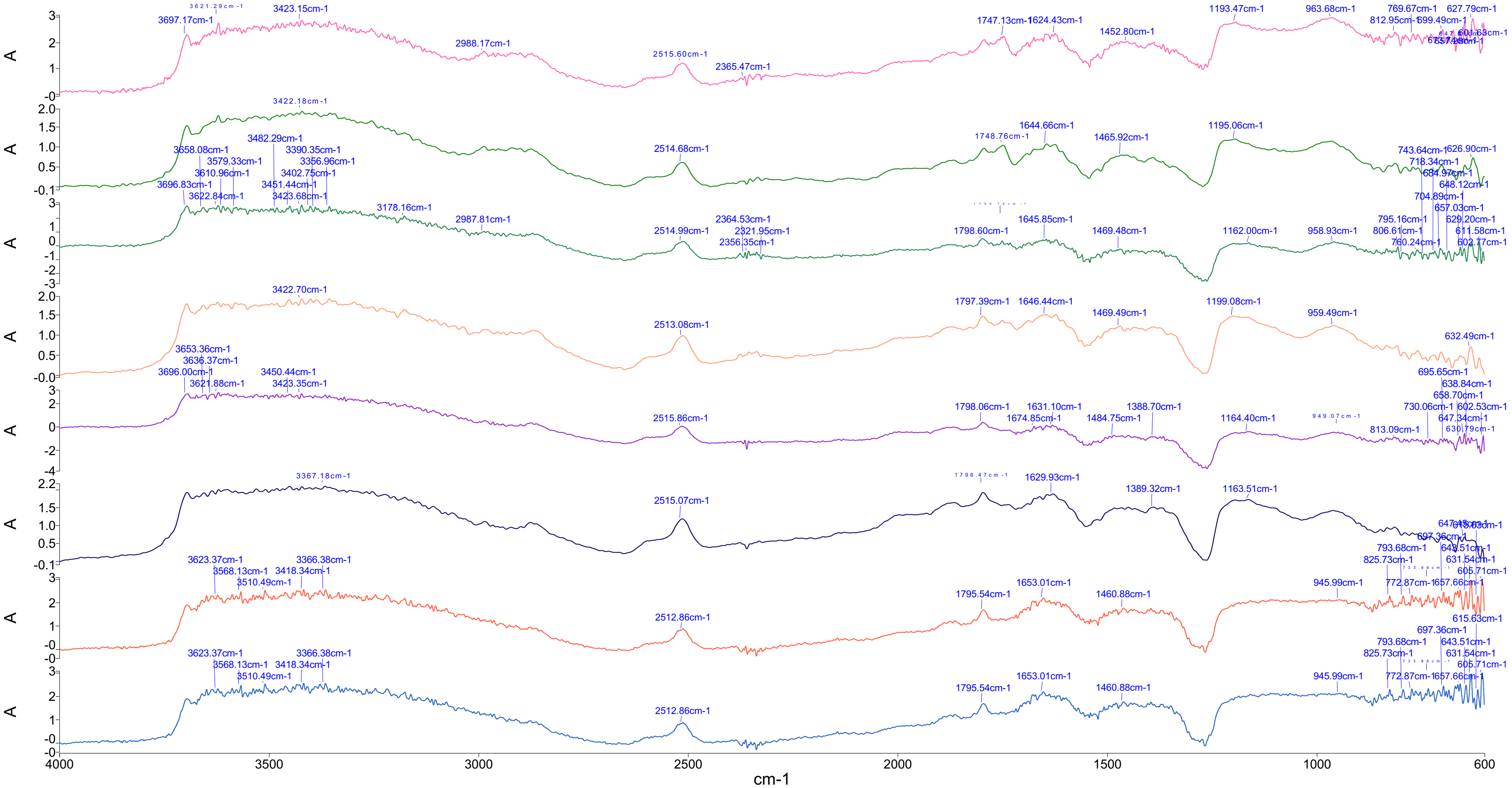
Çatalhöyük mudbrick (unit 18570, feature 5013, Building 79, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (red and blue); break-edge (pink and green) 1mm depth (yellow and purple); 5mm depth (navy and green).

U22158_s1



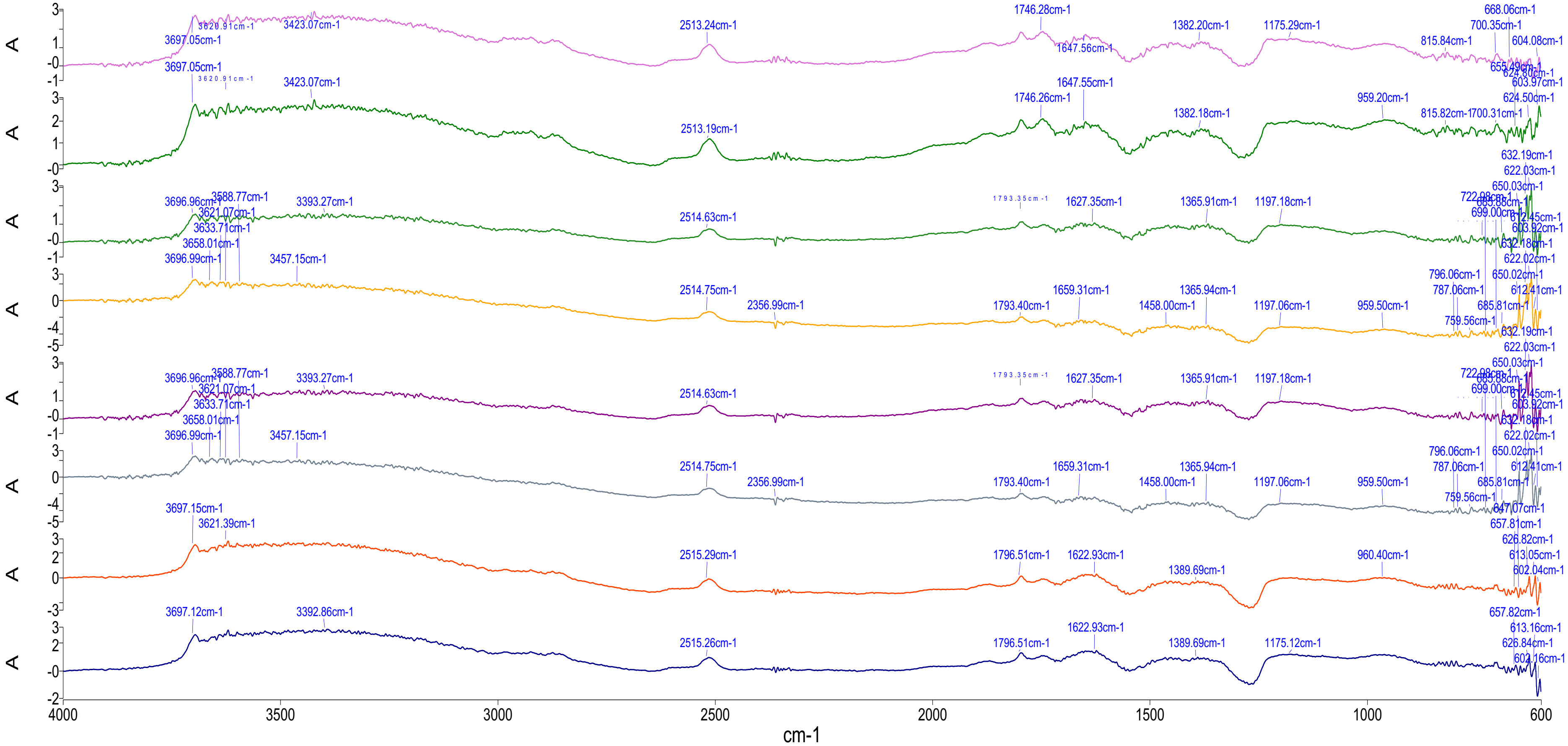
Çatalhöyük mudbrick (unit 22158, feature 230, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (red and pink); break-edge (green and yellow) 1mm depth (purple and black); 5mm depth (red and blue).

U22158_s2



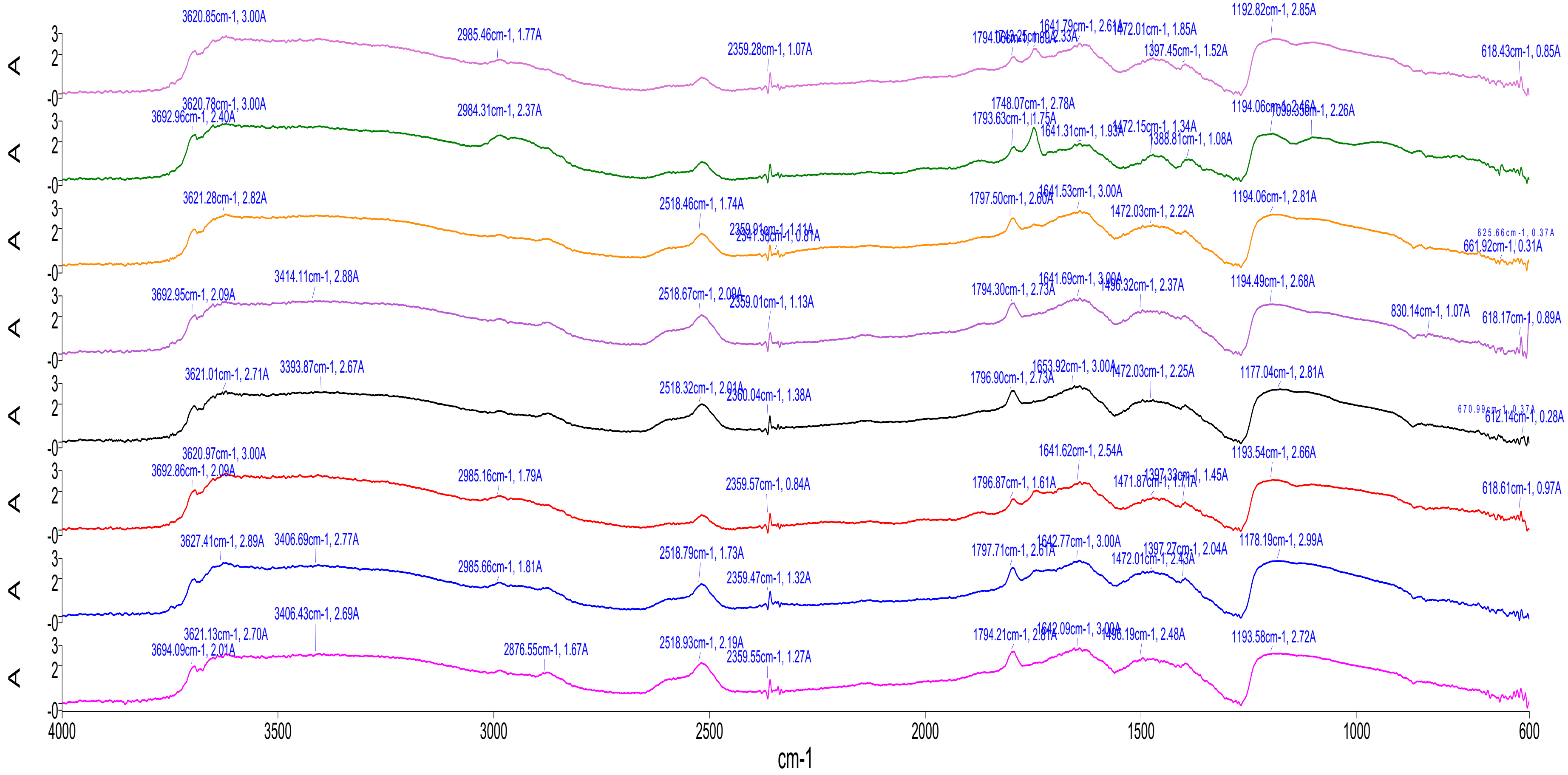
Çatalhöyük mudbrick (unit 22158, feature 230, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (green and yellow) 1mm depth (purple and black); 5mm depth (red and blue)

U21134_s15



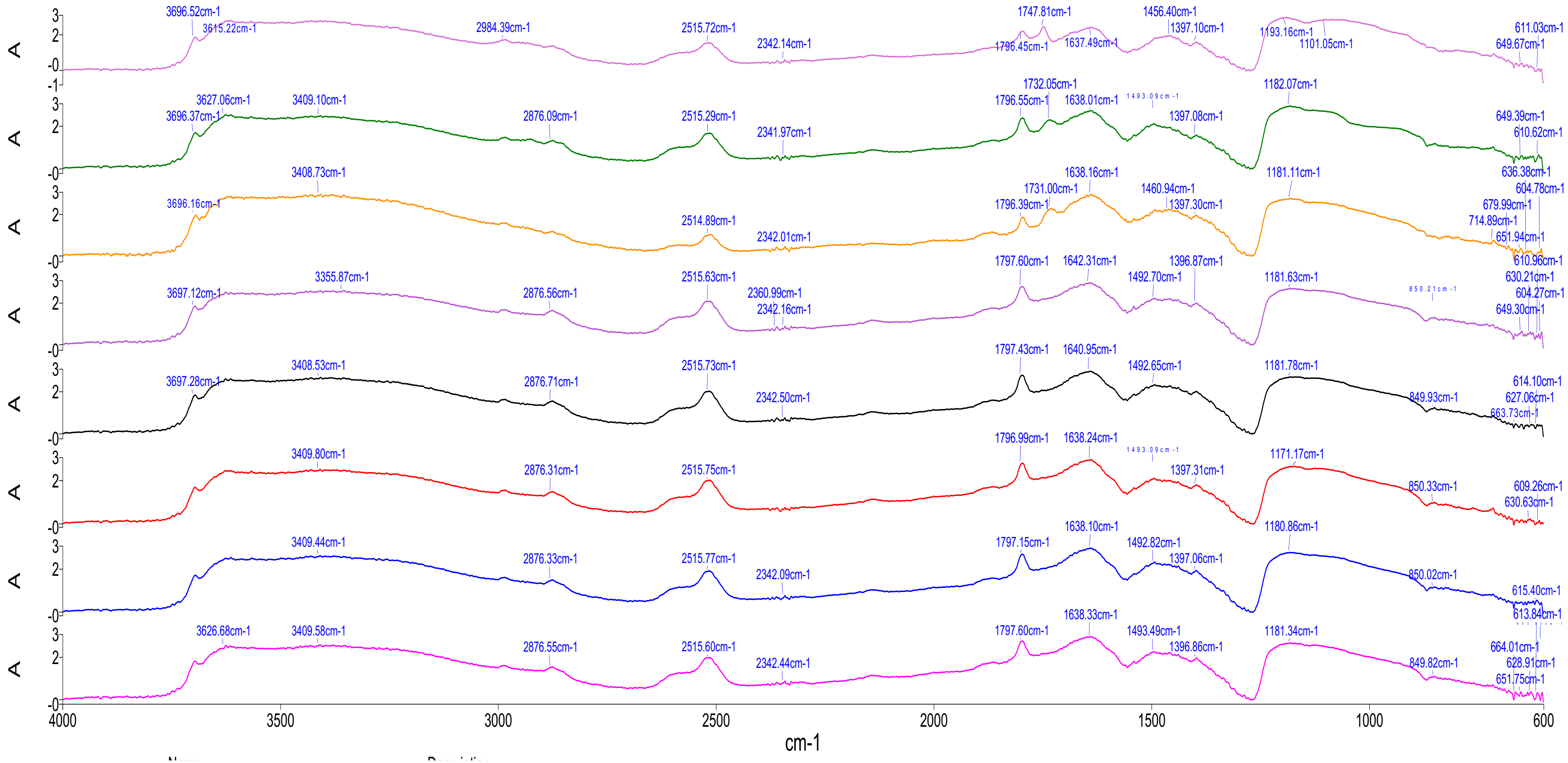
Çatalhöyük mudbrick (unit 21134, feature 255, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (green and yellow) 1mm depth (burgundy and grey); 5mm depth (red and blue).

U22339_s1



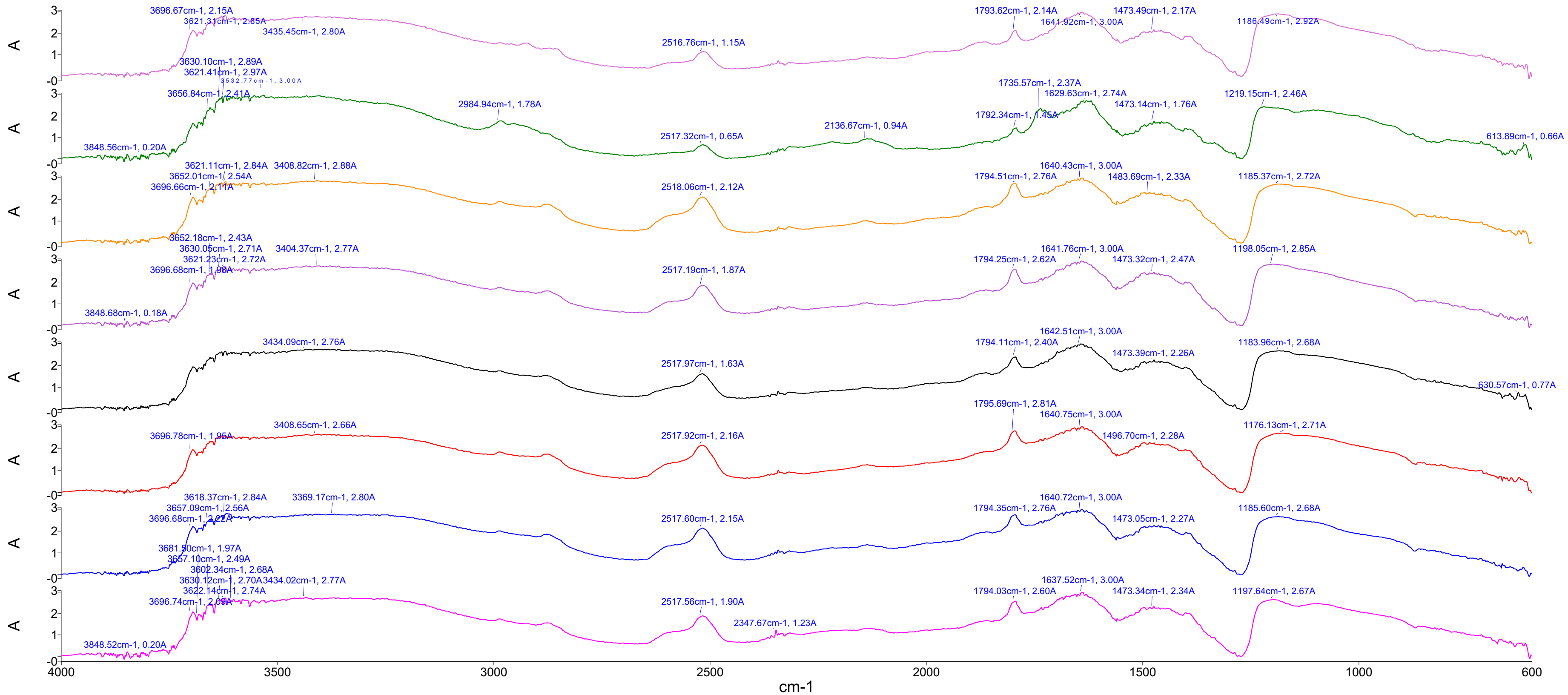
Çatalhöyük mudbrick (unit 22339, feature 3483, Building 89, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U22342_s1



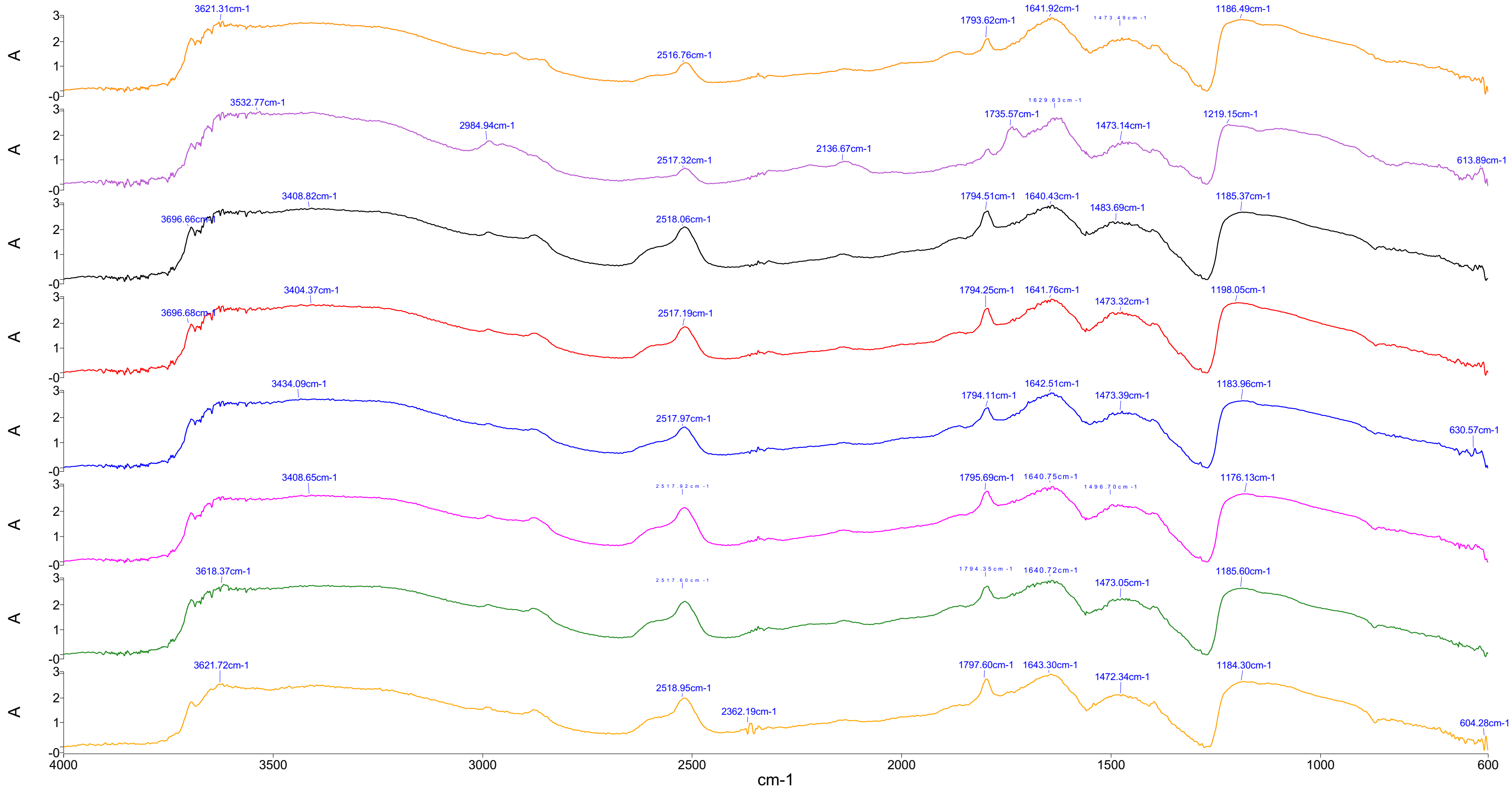
Çatalhöyük mudbrick (unit 22342, feature 3515, Building 96, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (red and pink); break-edge (green and yellow) 1mm depth (purple and black); 5mm depth (red and blue).

U22906_s1



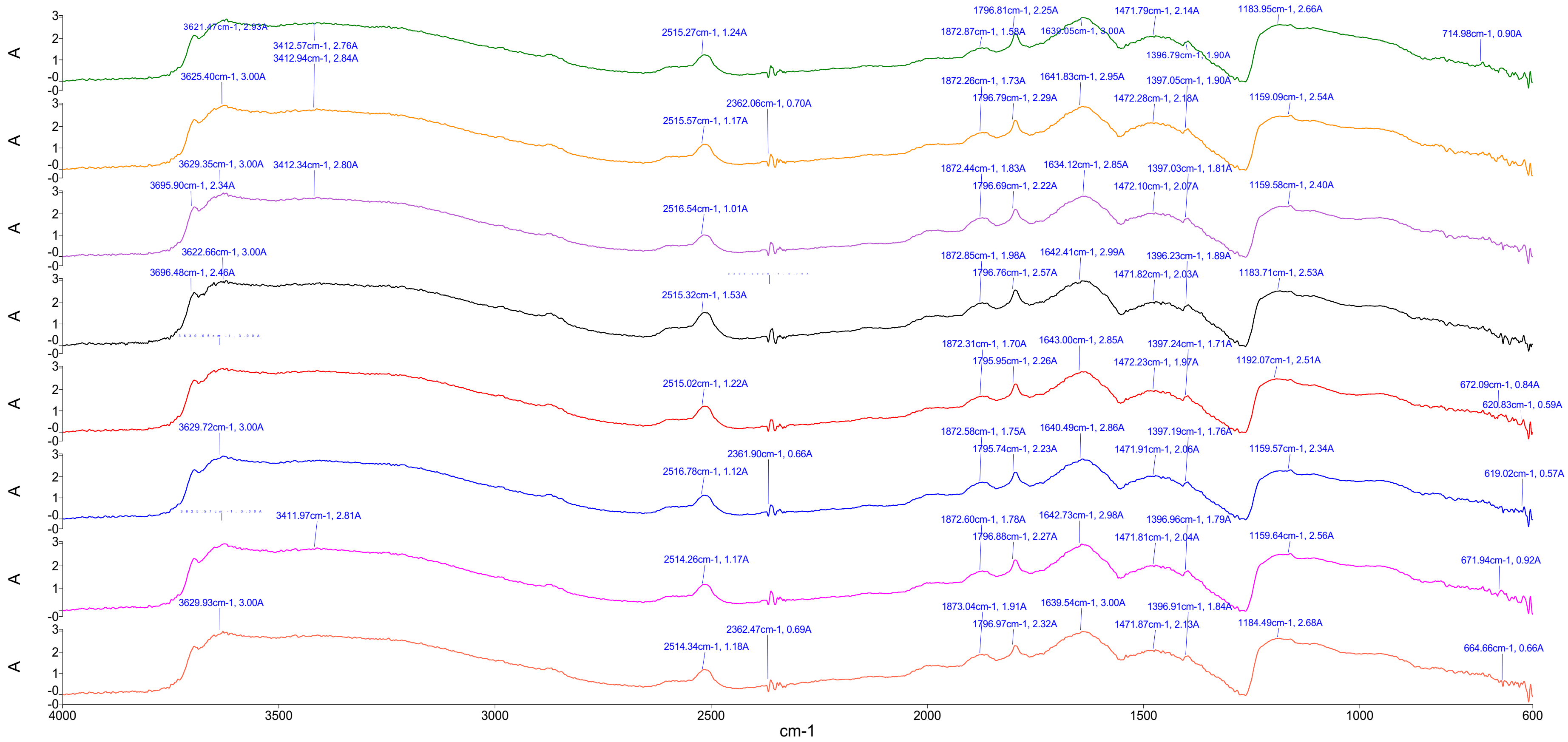
Çatalhöyük mudbrick (unit 22906, feature 4088, Building 97, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (yellow and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U22906_s2



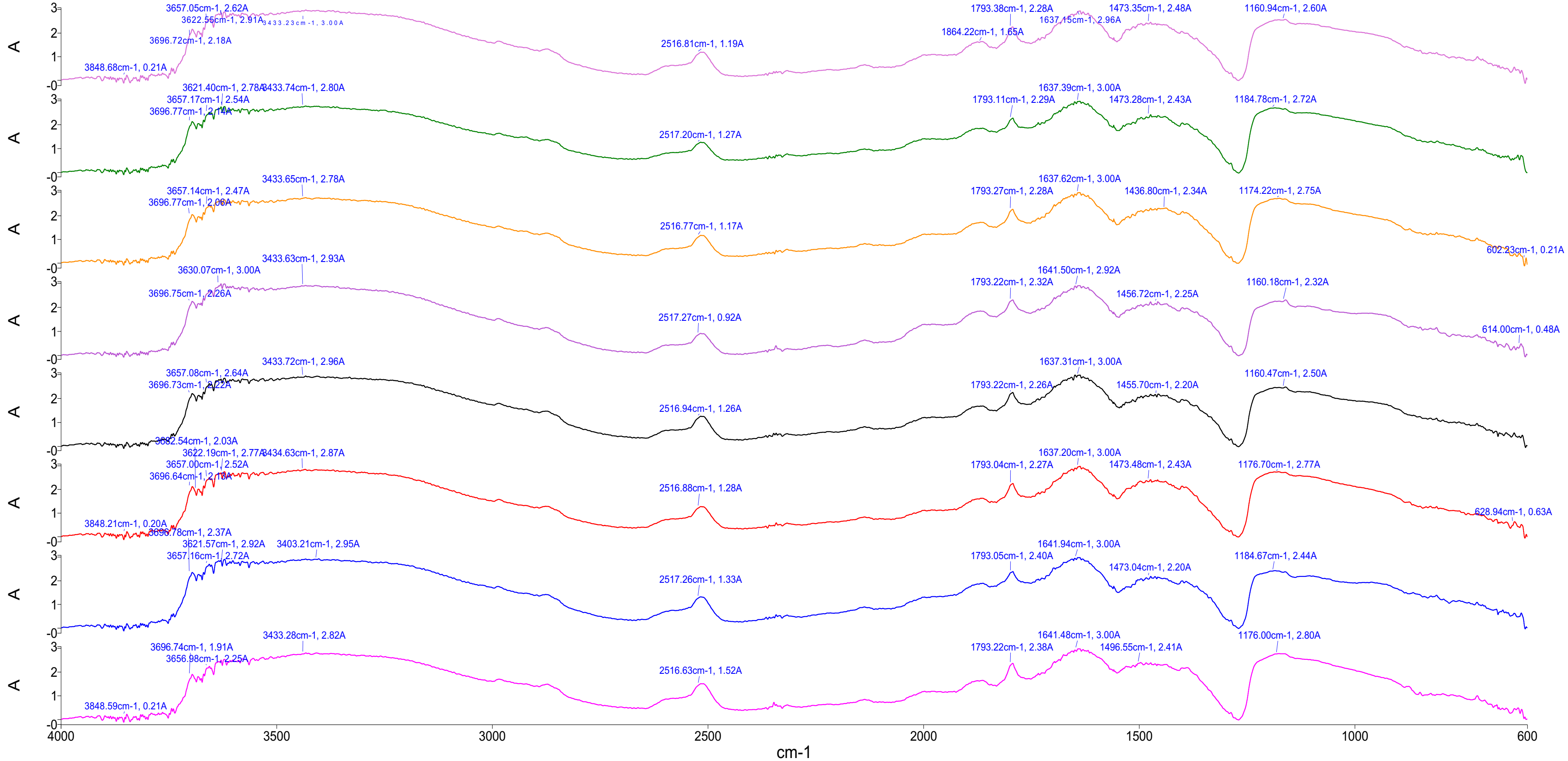
Çatalhöyük mudbrick (unit 22906, feature 4088, Building 97, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (yellow and purple); break-edge (black and red) 1mm depth (blue and pink); 5mm depth (green and yellow).

U12321_s4



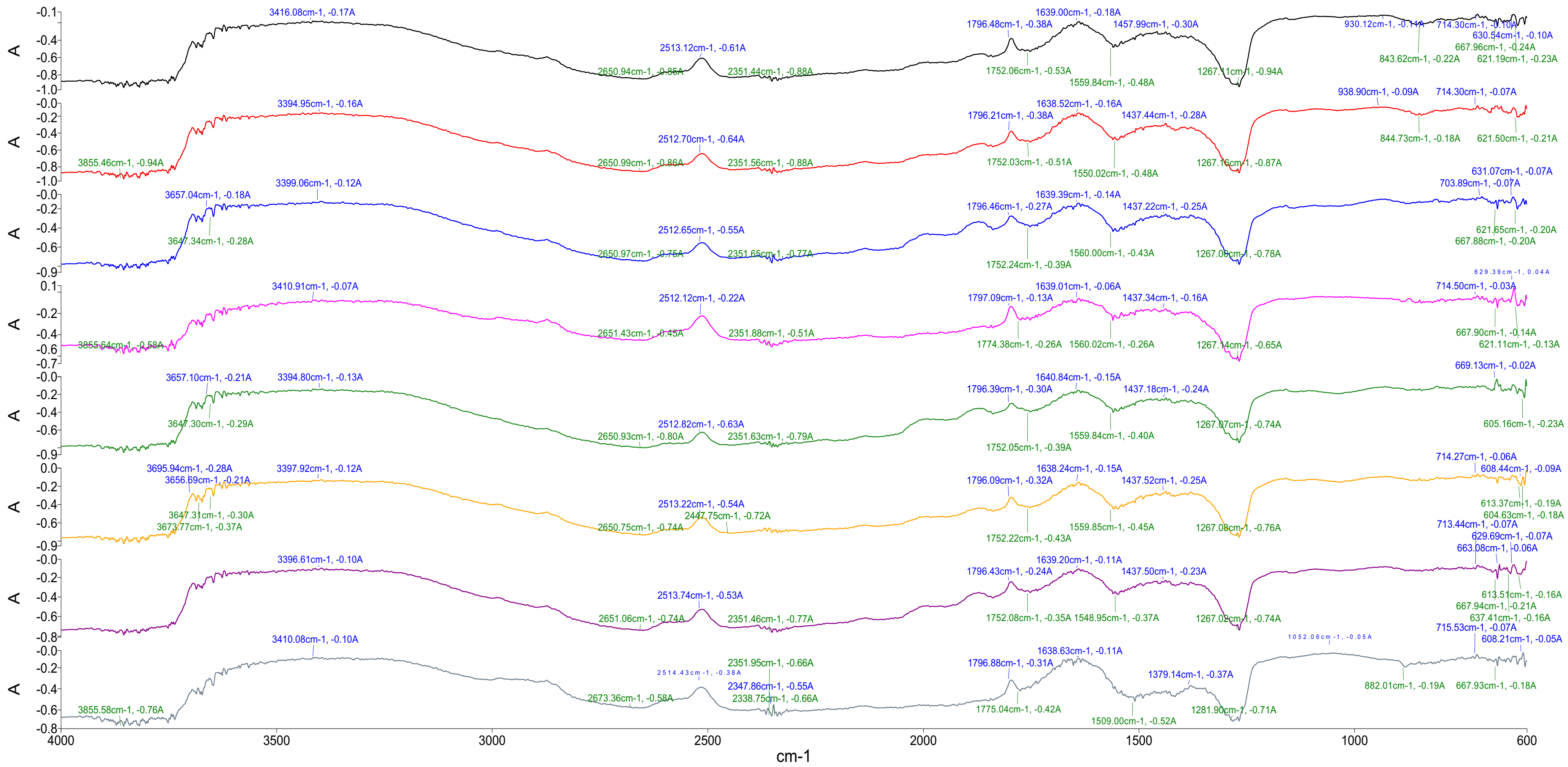
Çatalhöyük mudbrick (unit 12321, feature 1591, Building 55, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (green and yellow); break-edge (purple and black) 1mm depth (red and blue); 5mm depth (pink and orange).

U13694_s14



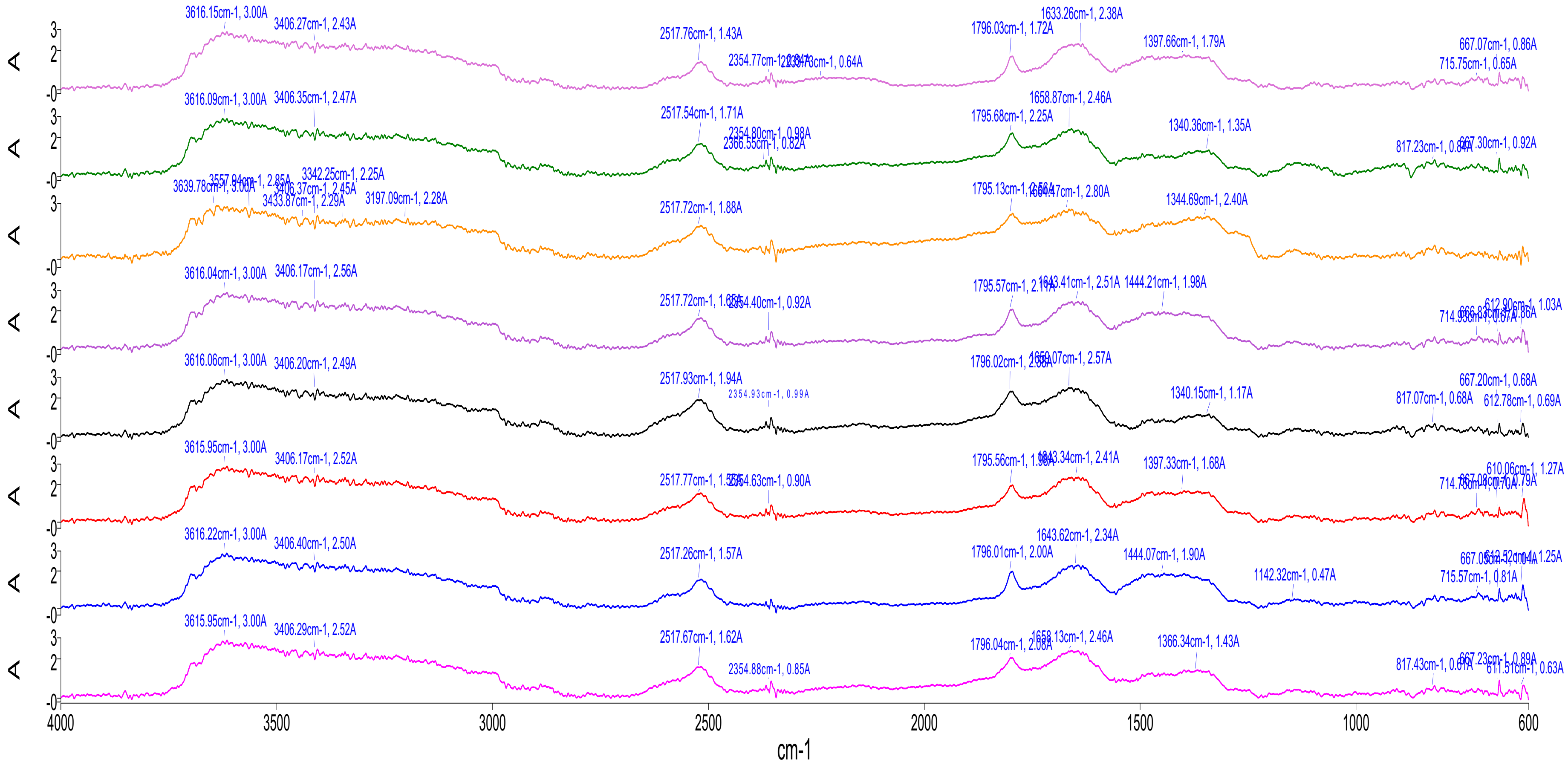
Çatalhöyük mudbrick (unit 13694, feature 1657, Building 49, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (yellow and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U14160_s3



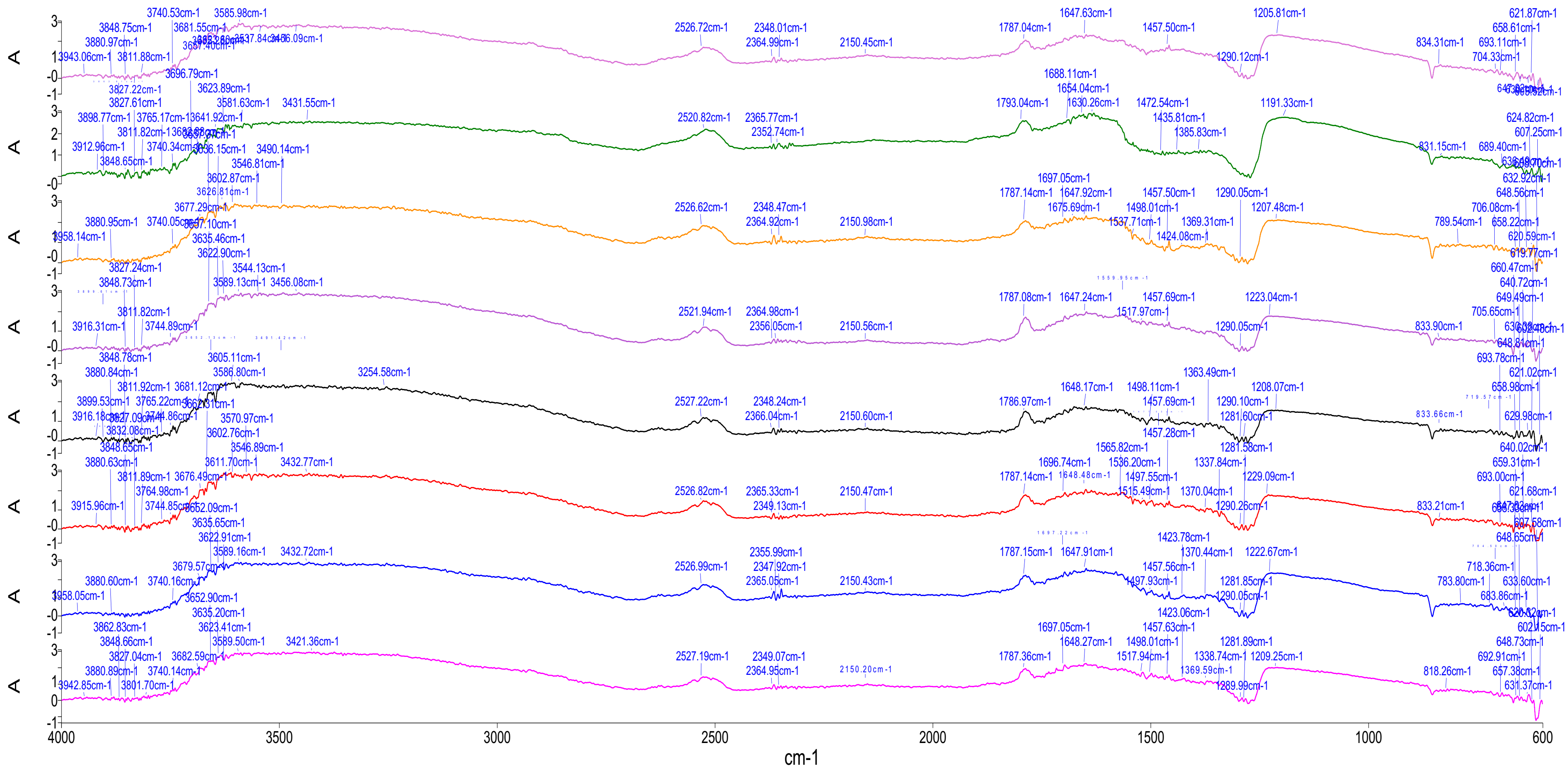
Çatalhöyük mudbrick (unit 14160, feature 2211, Building 52, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (black and red); break-edge (blue and pink) 1mm depth (green and yellow); 5mm depth (burgundy and grey).

U16370_s1



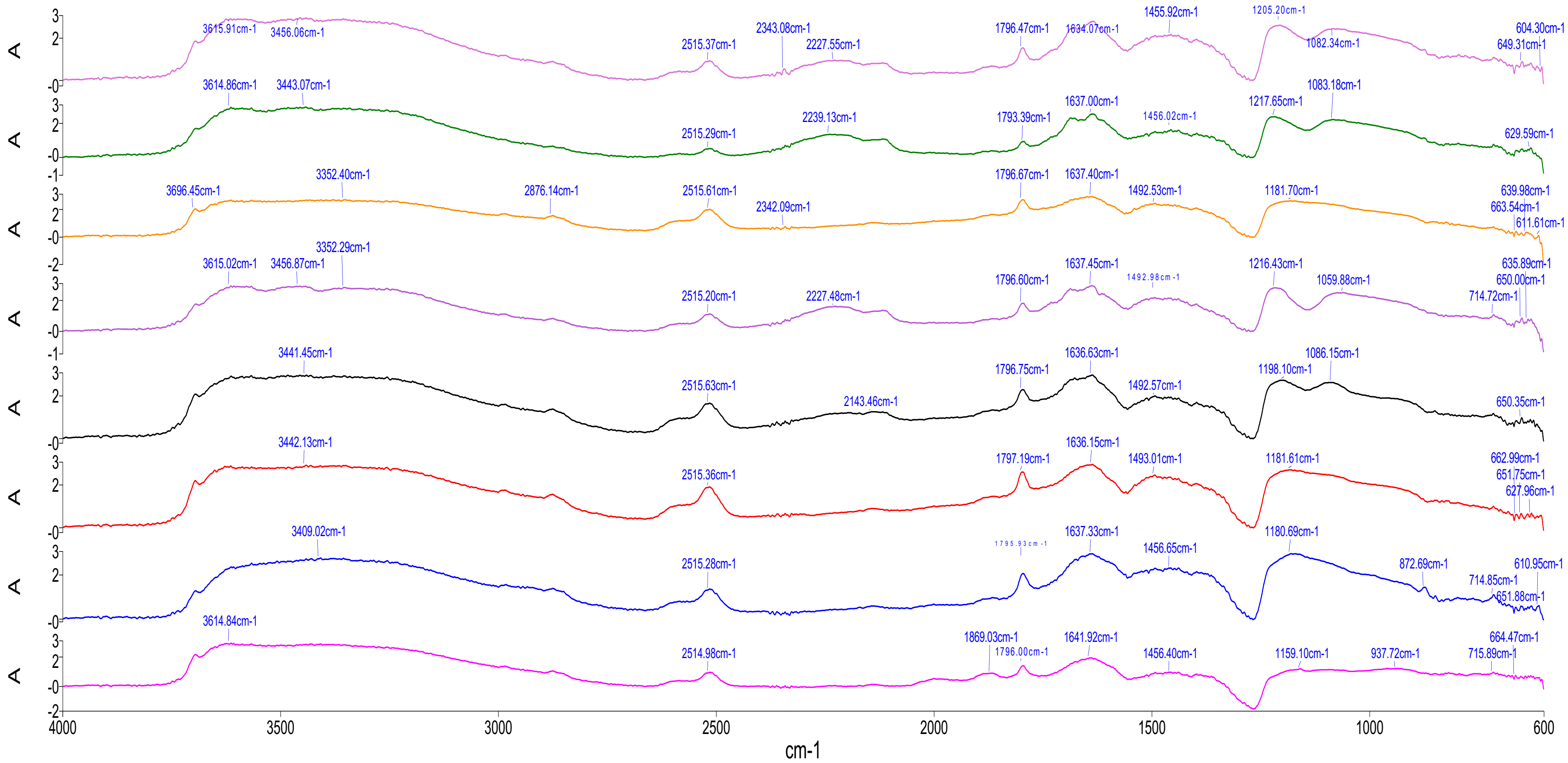
Çatalhöyük mudbrick (unit 16370, feature 1591, Building 55, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U17589_s4



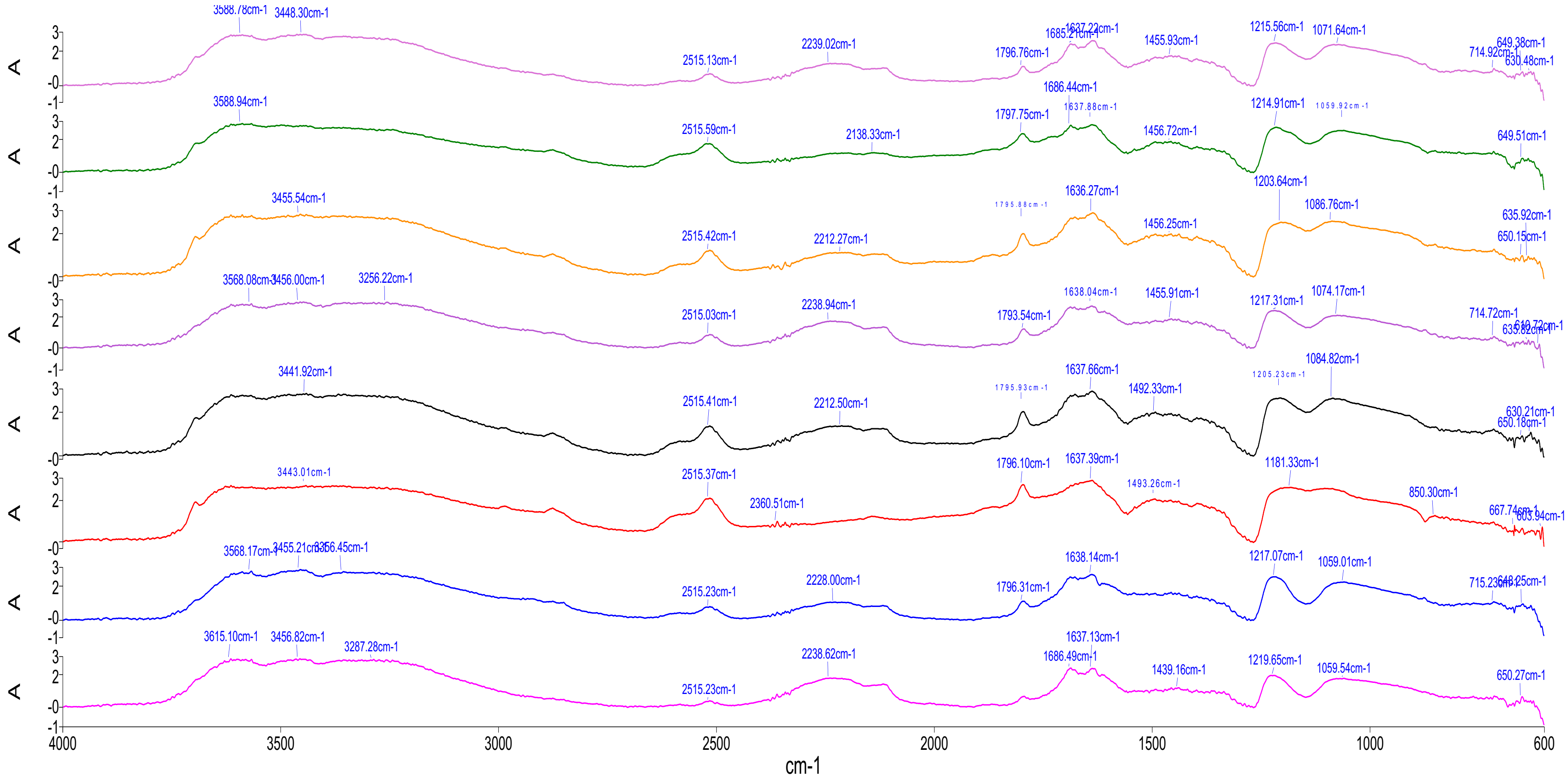
Çatalhöyük mudbrick (unit 17598, feature 3097, Building 77, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U17745_s1



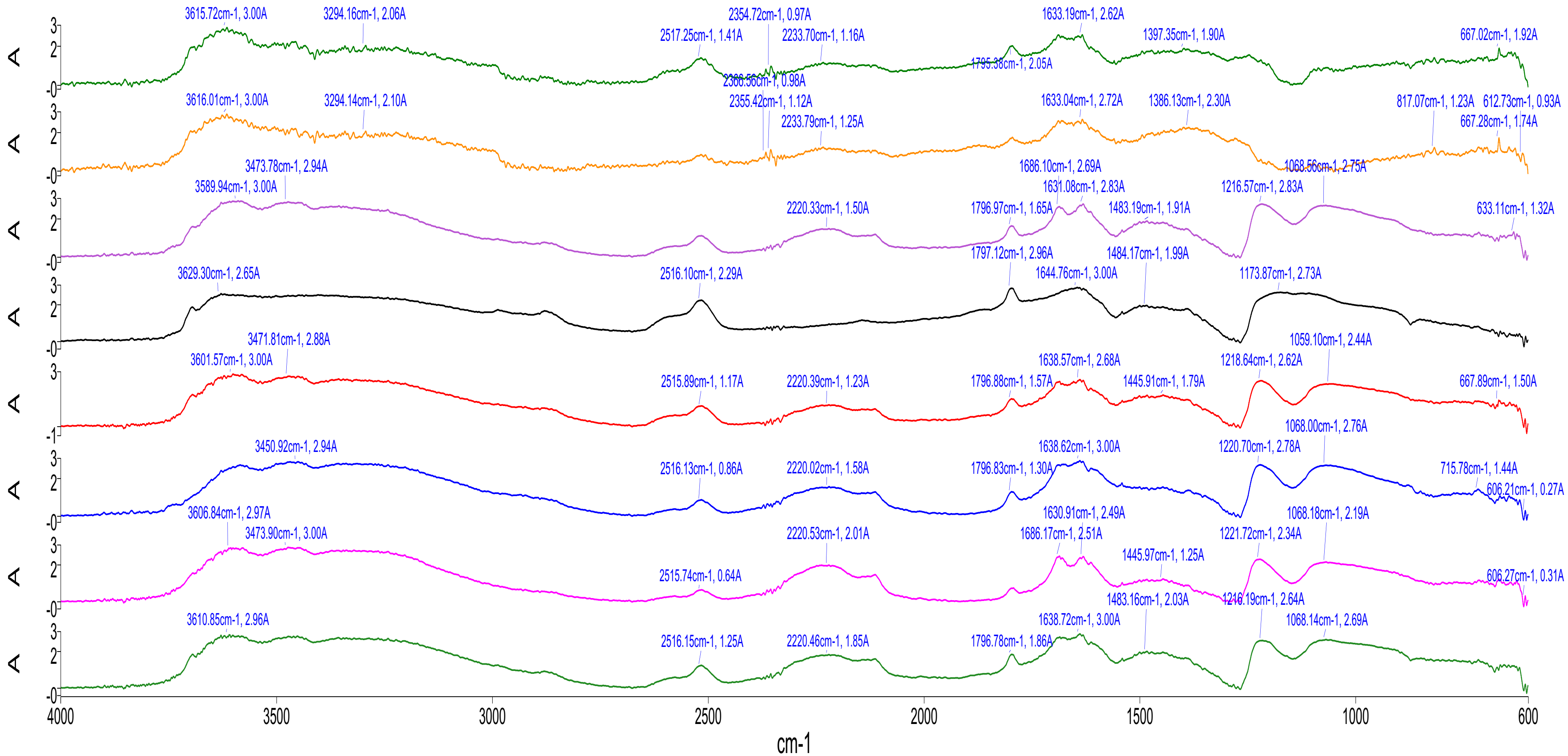
Çatalhöyük mudbrick (unit 17745, feature 1614, Building 82, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U17745_s2



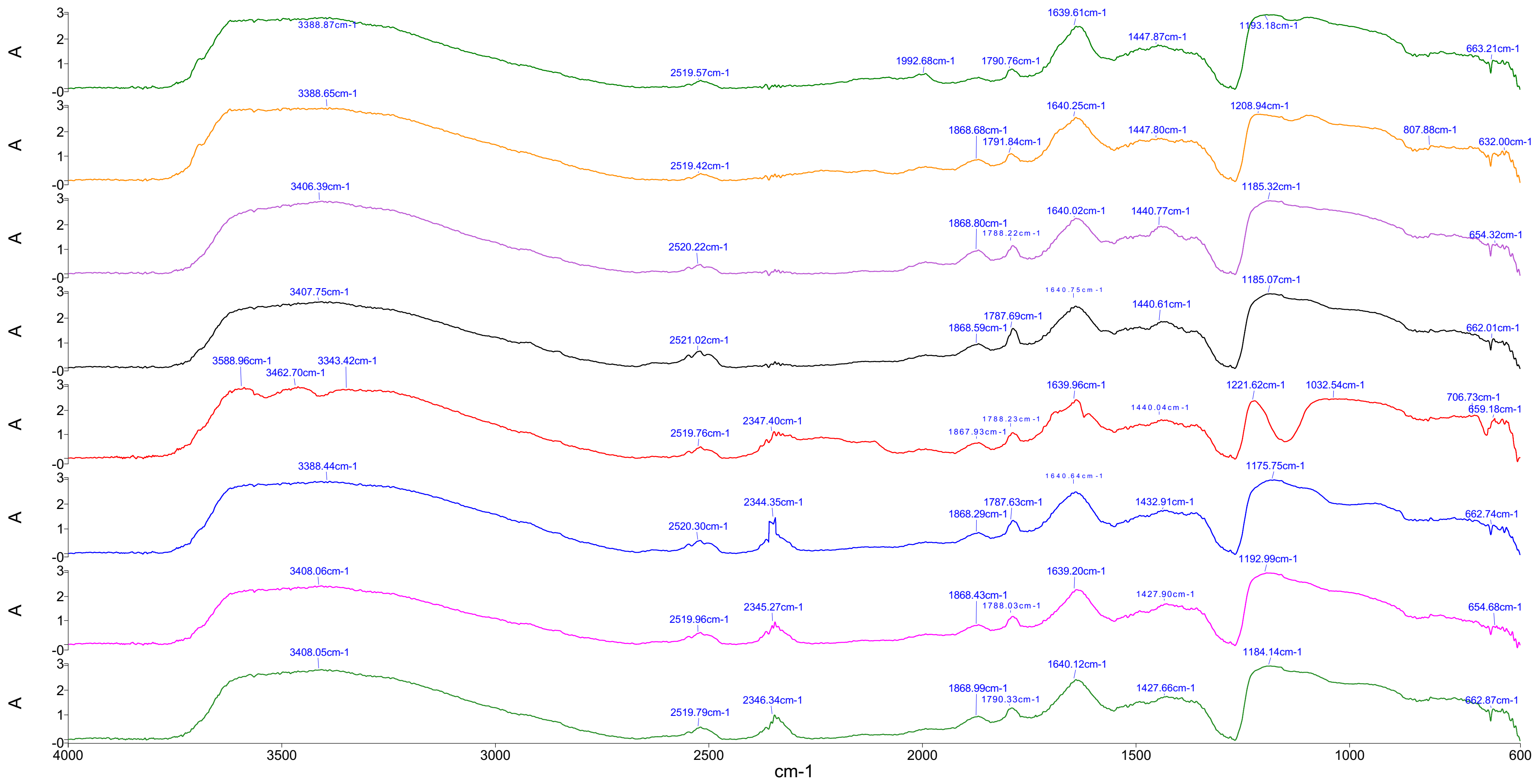
Çatalhöyük mudbrick (unit 17745, feature 1614, Building 82, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U17749_s1



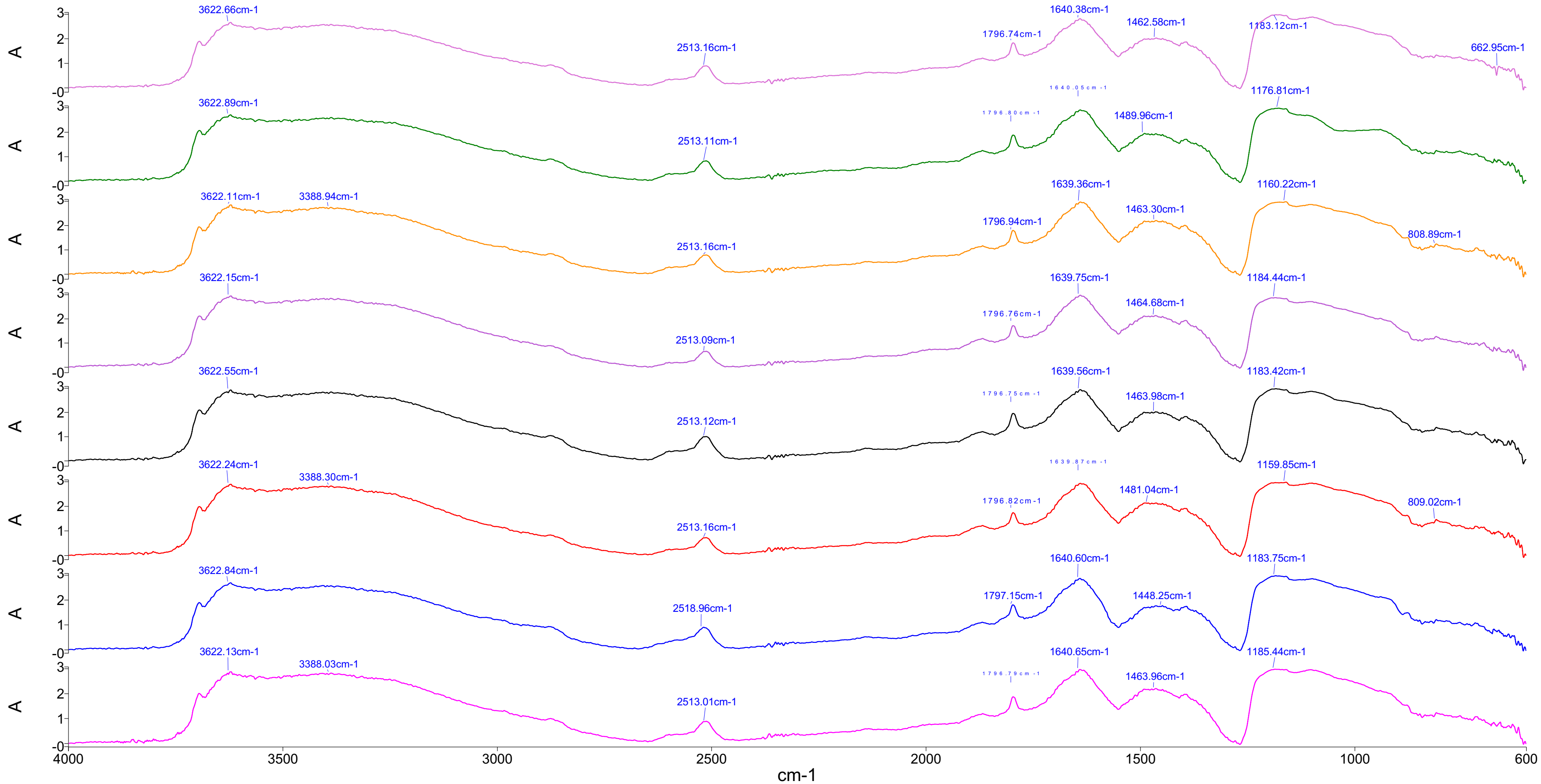
Çatalhöyük mudbrick (unit 17745, feature 1613, Building 82, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (green and yellow); break-edge (purple and black) 1mm depth (red and blue); 5mm depth (pink and green).

U17994_s1



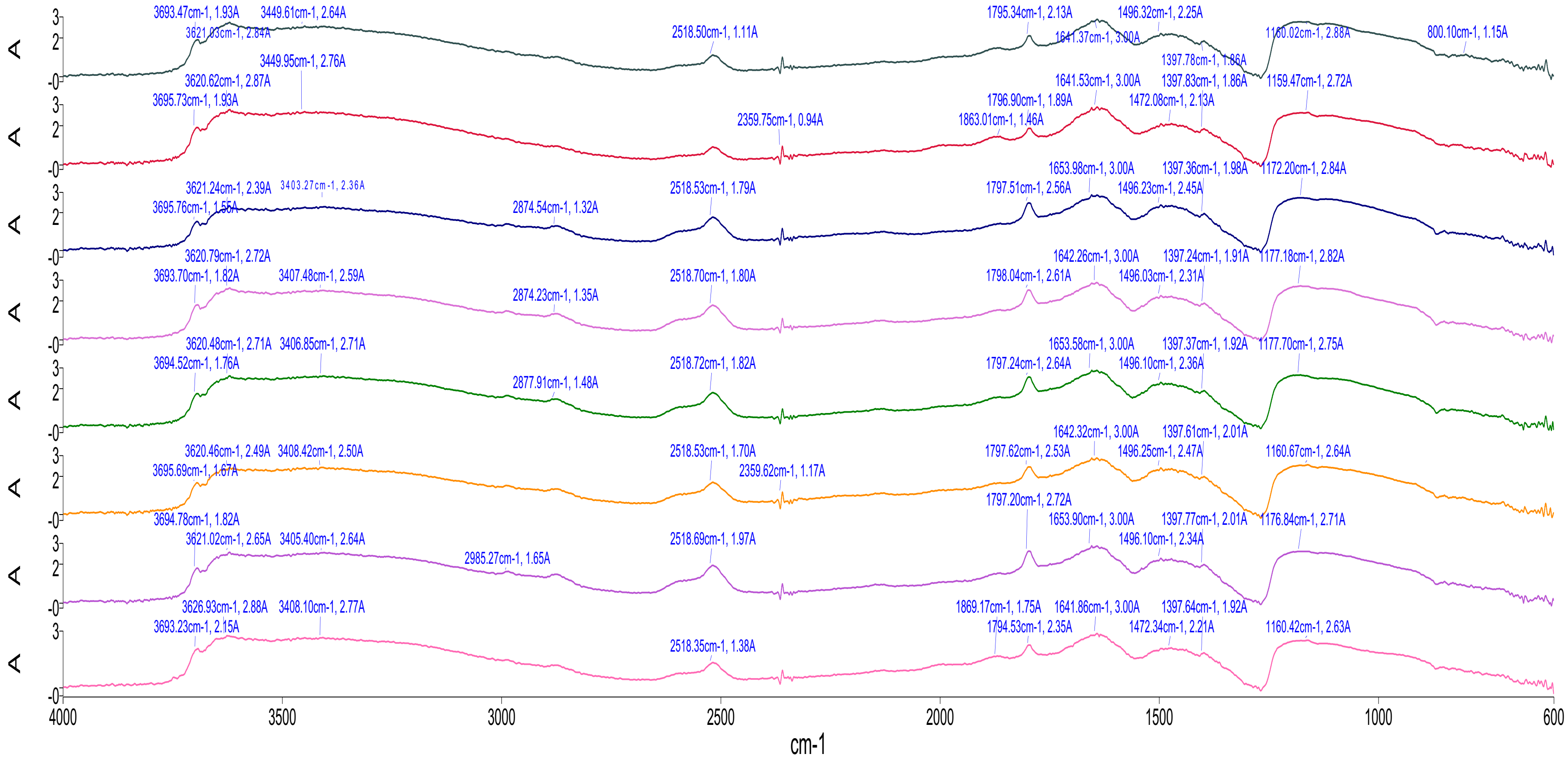
Çatalhöyük mudbrick (unit 17994, feature 5013, Building 79, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (green and yellow); break-edge (purple and black) 1mm depth (red and blue); 5mm depth (pink and green).

U18670_s1



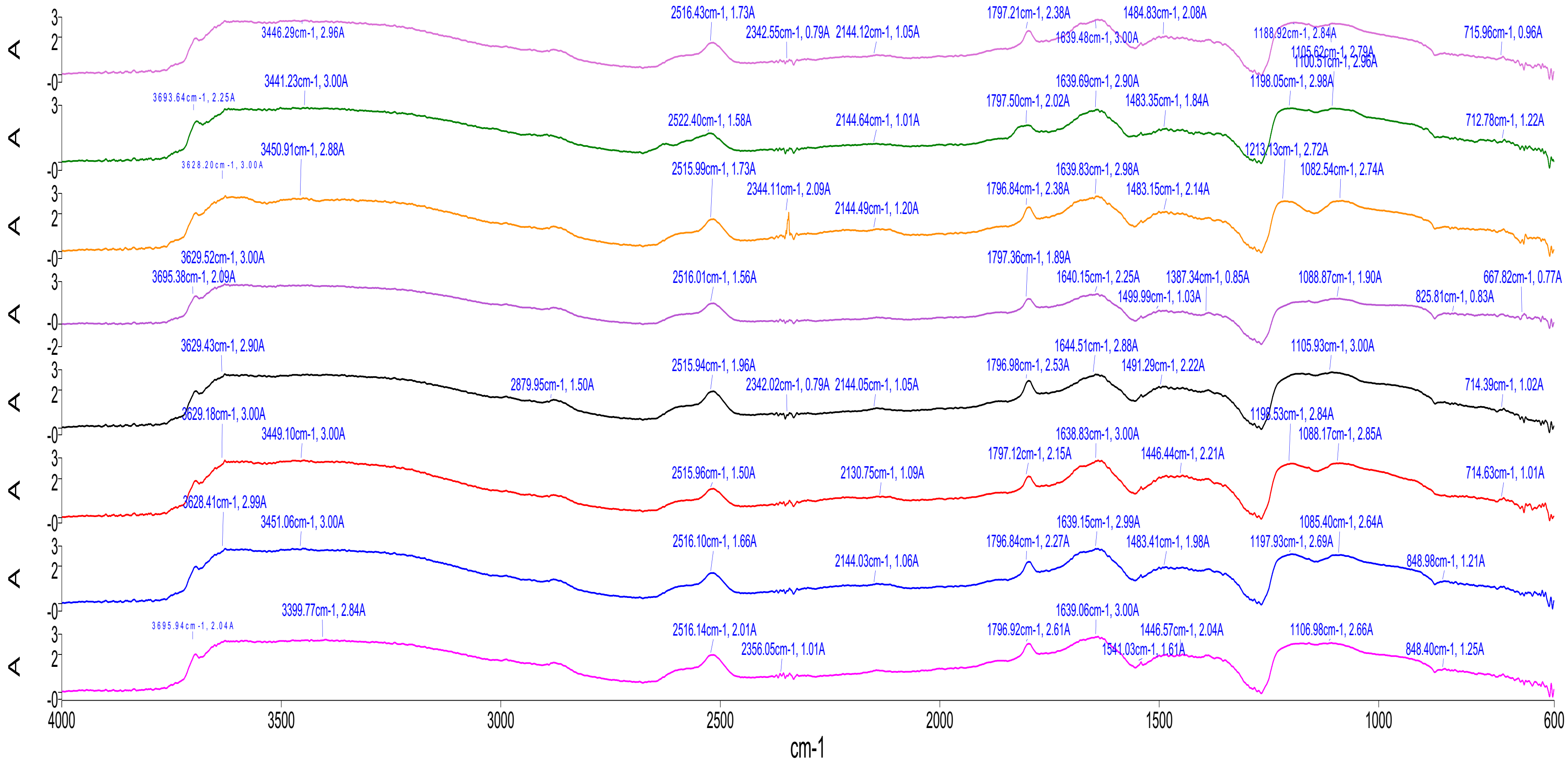
Çatalhöyük mudbrick (unit 18670, feature 4086, Building 97, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U18670_s2



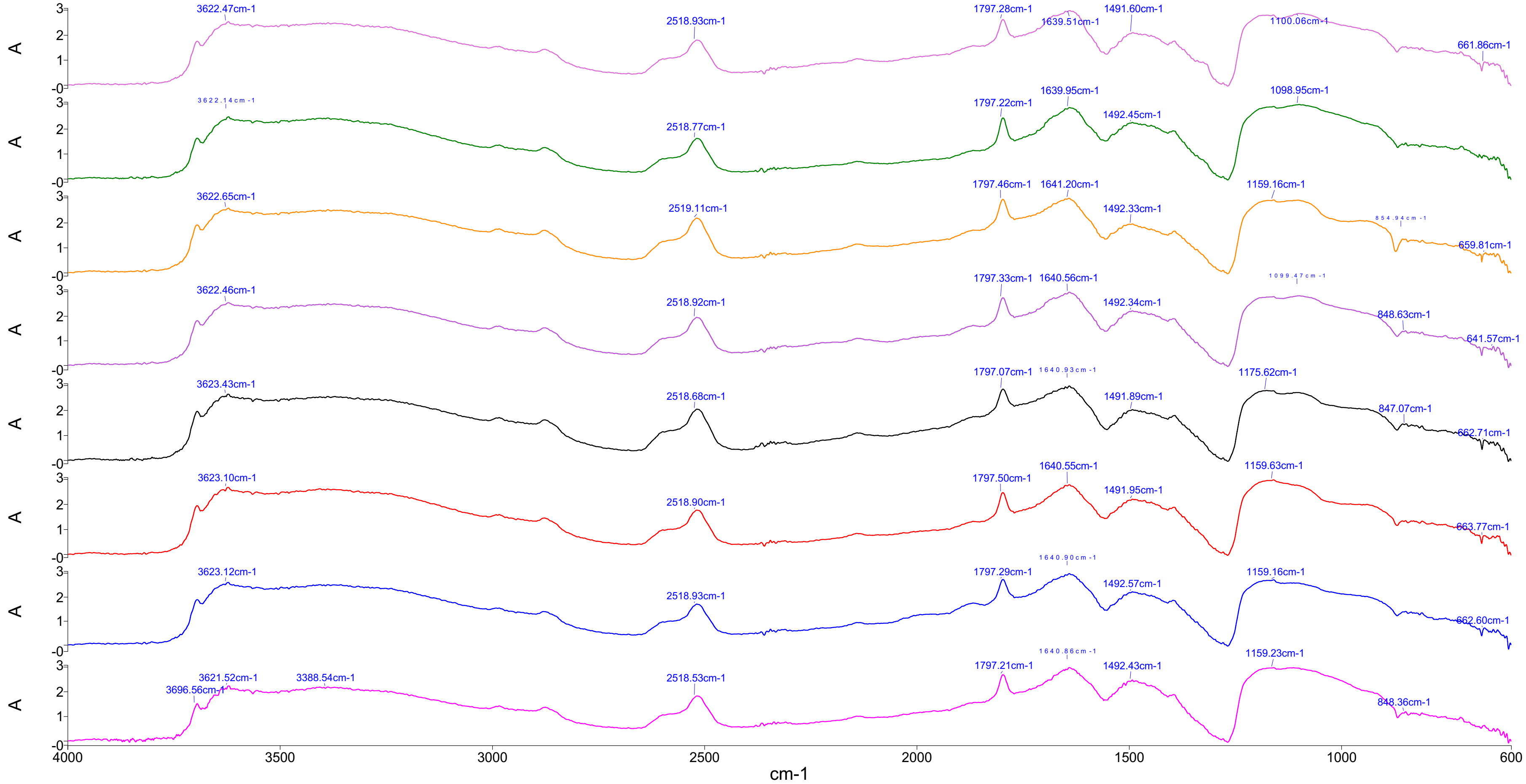
Çatalhöyük mudbrick (unit 18670, feature 4086, Building 97, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (grey and red); break-edge (navy and pink) 1mm depth (green and orange); 5mm depth (purple and pink).

U20568_s4



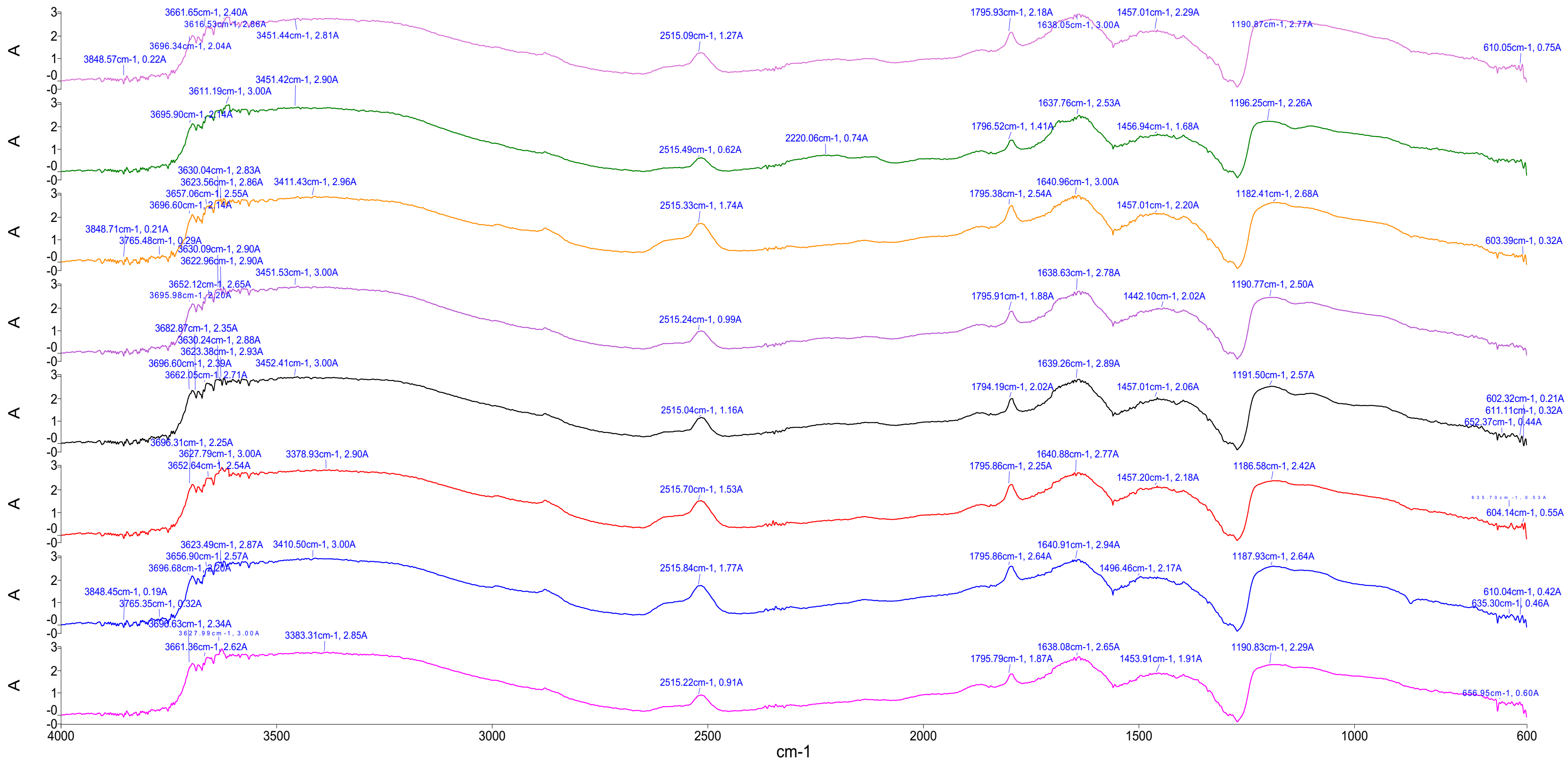
Çatalhöyük mudbrick (unit 20568, feature 1024, Building 114, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U20589_s1



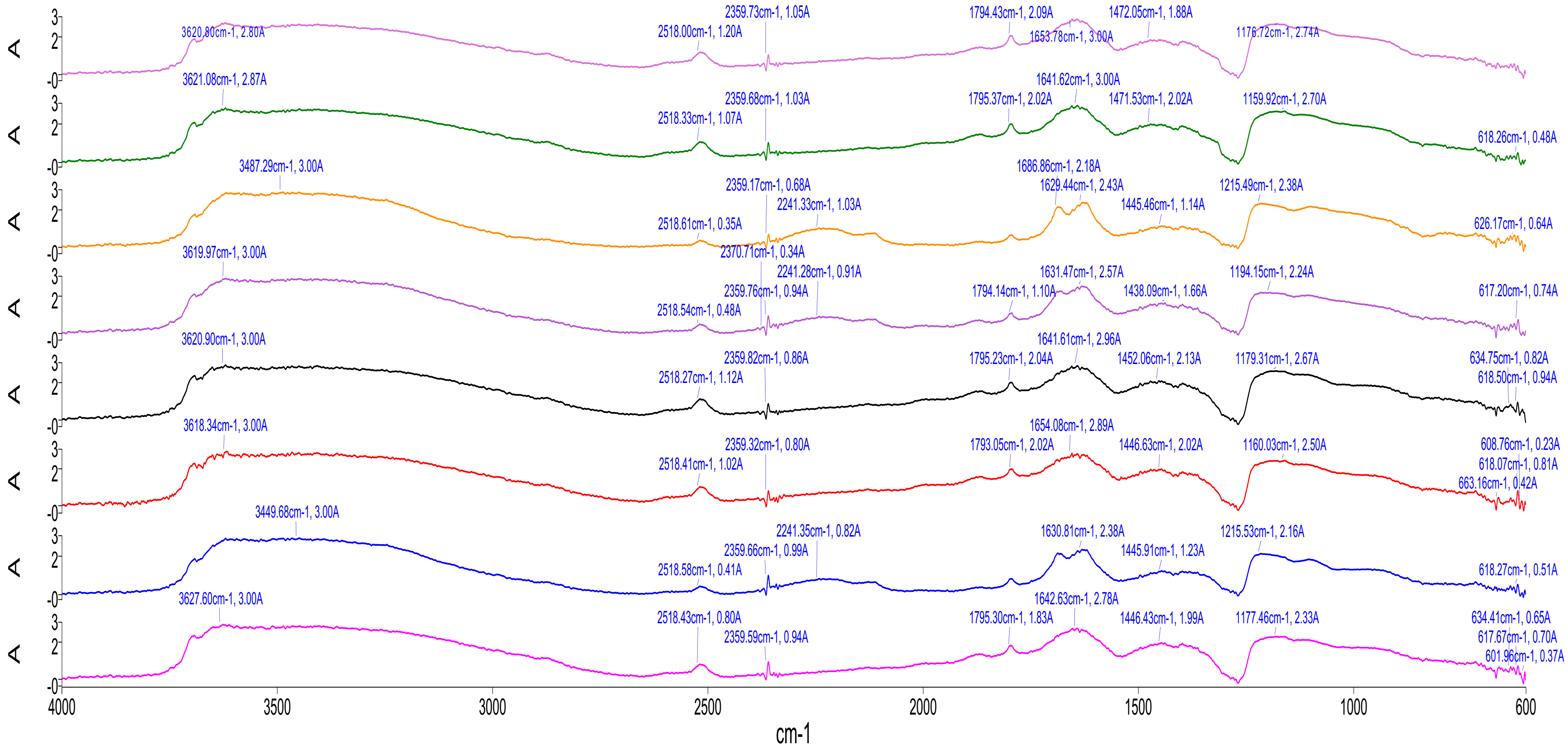
Çatalhöyük mudbrick (unit 20589, feature 297, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U20590_s1



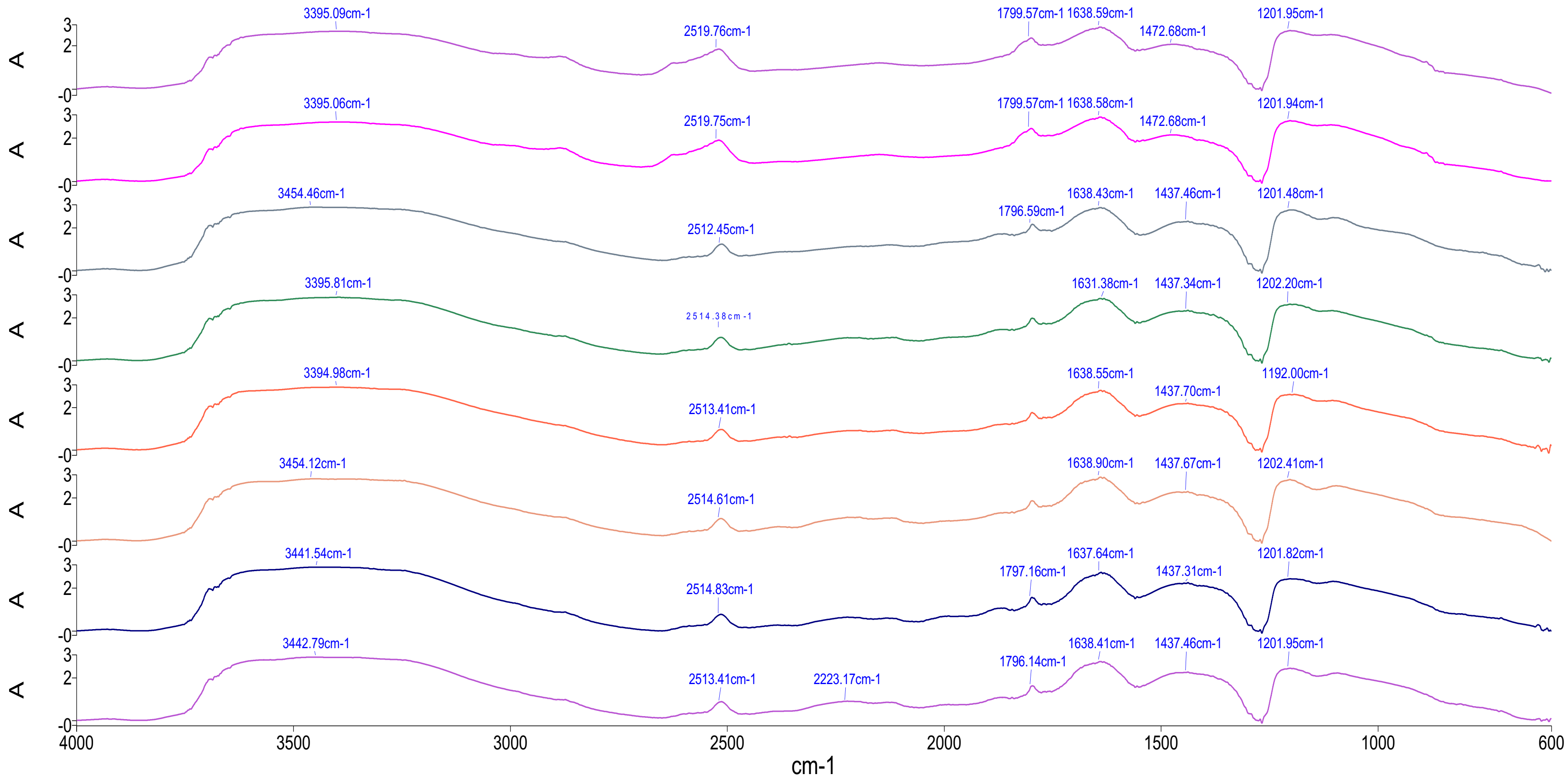
Çatalhöyük mudbrick (unit 20590, feature 294, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U20591_s1



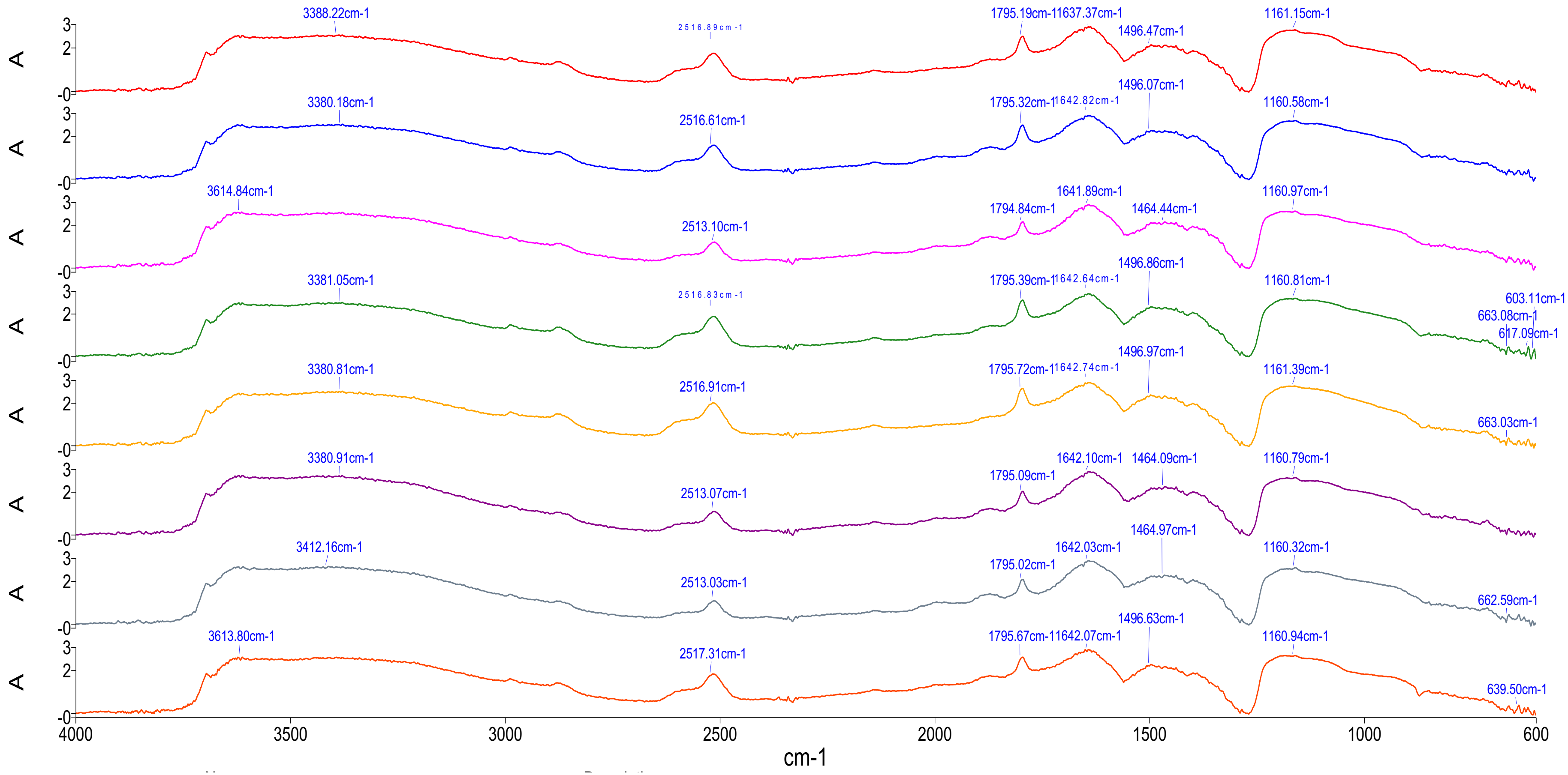
Çatalhöyük mudbrick (unit 20591, feature 97, Building 4, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and green); break-edge (orange and burgundy) 1mm depth (black and red); 5mm depth (blue and pink).

U20592_s1



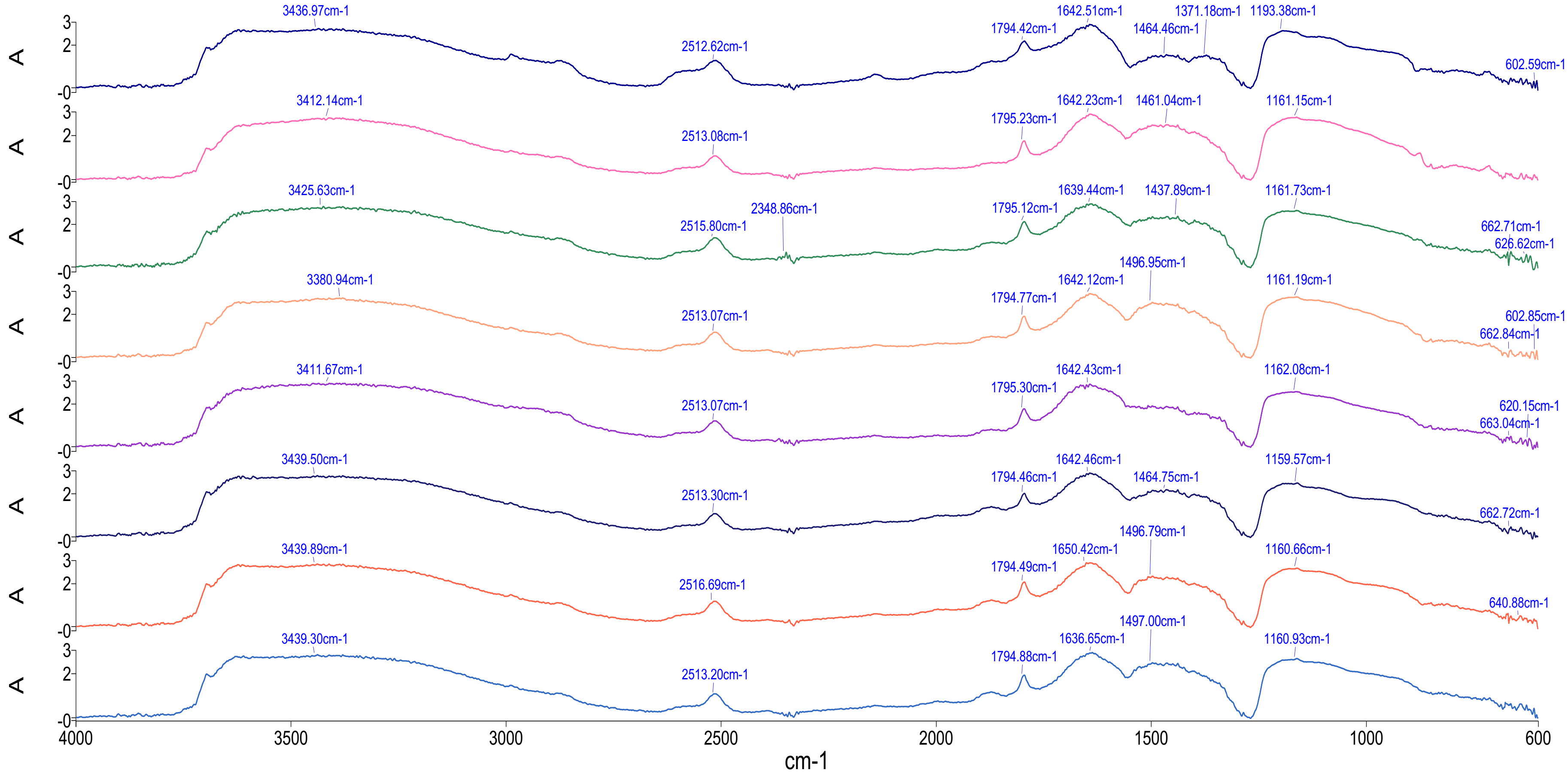
Çatalhöyük mudbrick (unit 20592, feature 2015, Building 52, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (purple and pink); break-edge (grey and green) 1mm depth (orange and yellow); 5mm depth (navy and purple).

U20593_s1



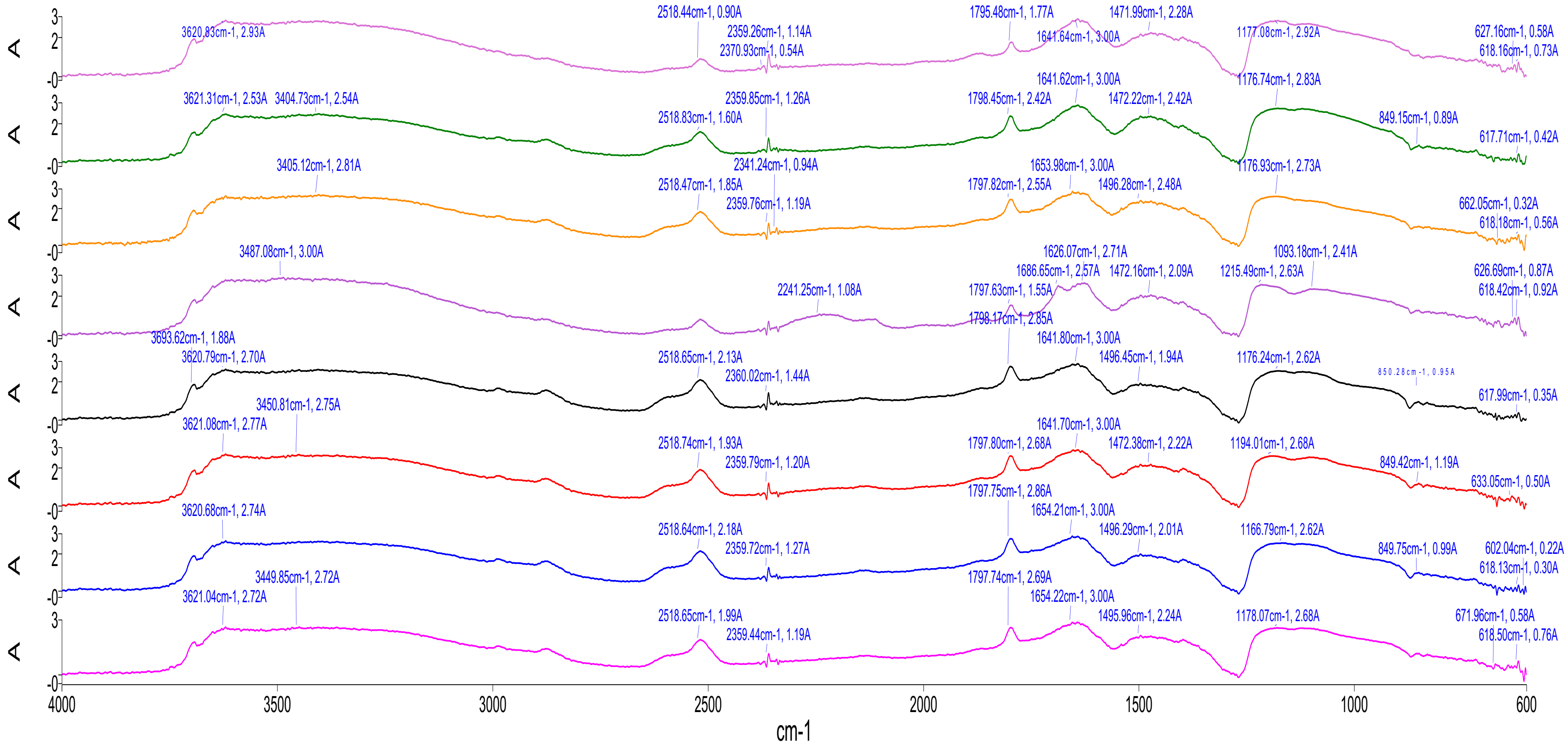
Çatalhöyük mudbrick (unit 20593, feature 2138, Building 54, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (red and blue); break-edge (pink and green) 1mm depth (yellow and burgundy); 5mm depth (grey and red).

U20594_s1



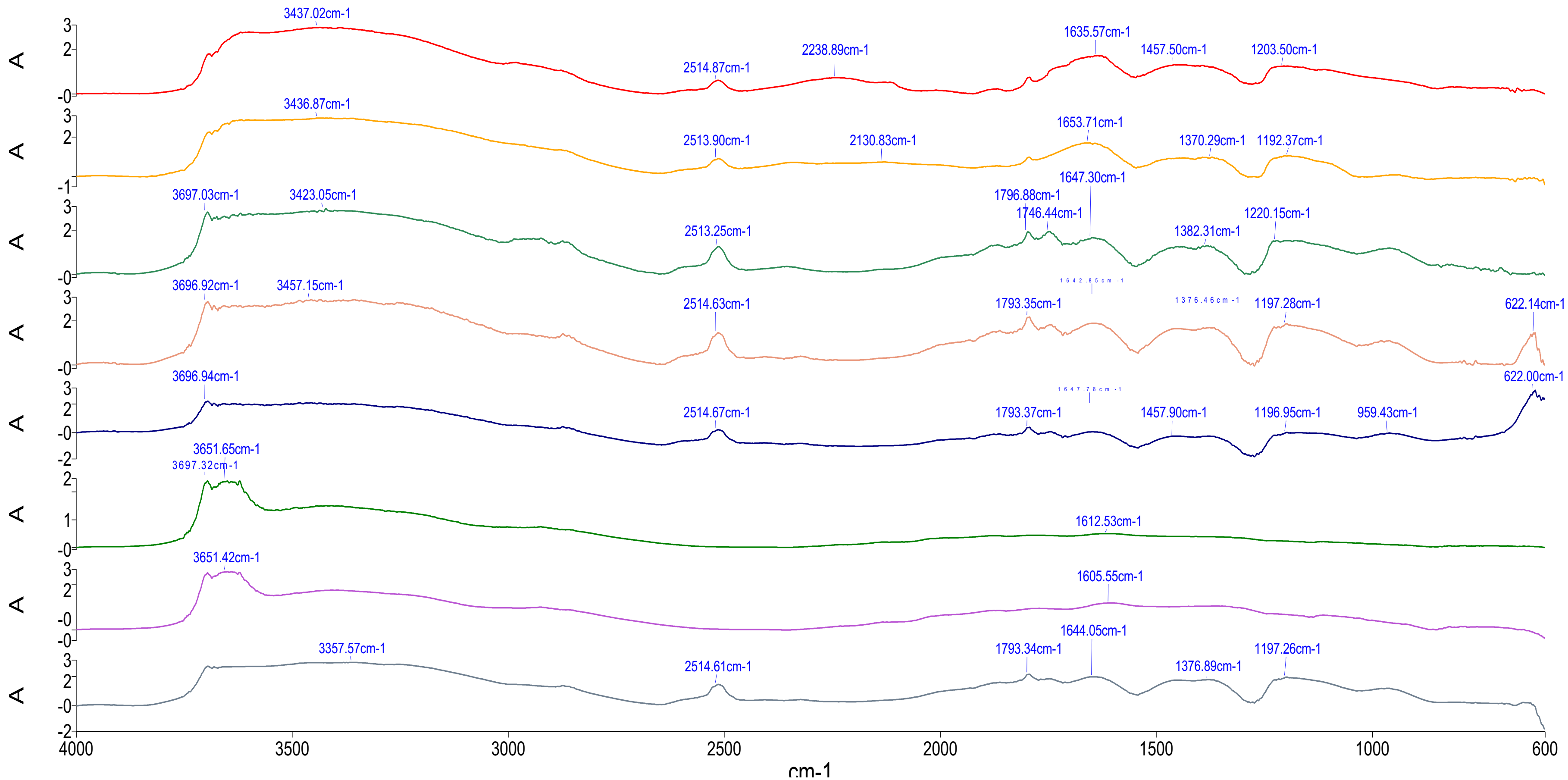
Çatalhöyük mudbrick (unit 20594, feature 3682, Building 114, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (navy and pink); break-edge (green and yellow) 1mm depth (purple and black); 5mm depth (orange and blue).

U20595_s1



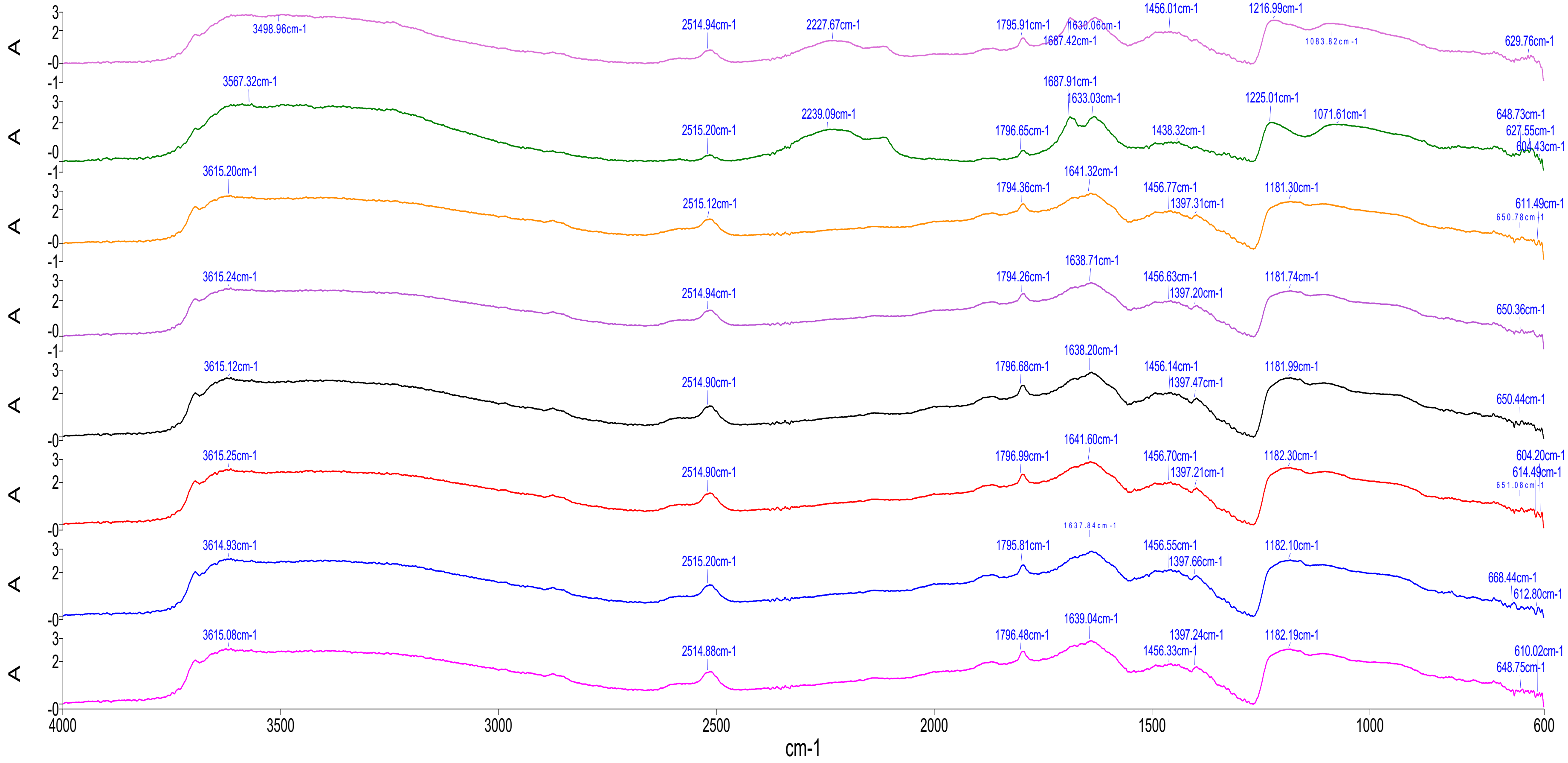
Çatalhöyük mudbrick (unit 20595, feature 1577, Building 51, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U21134_s14



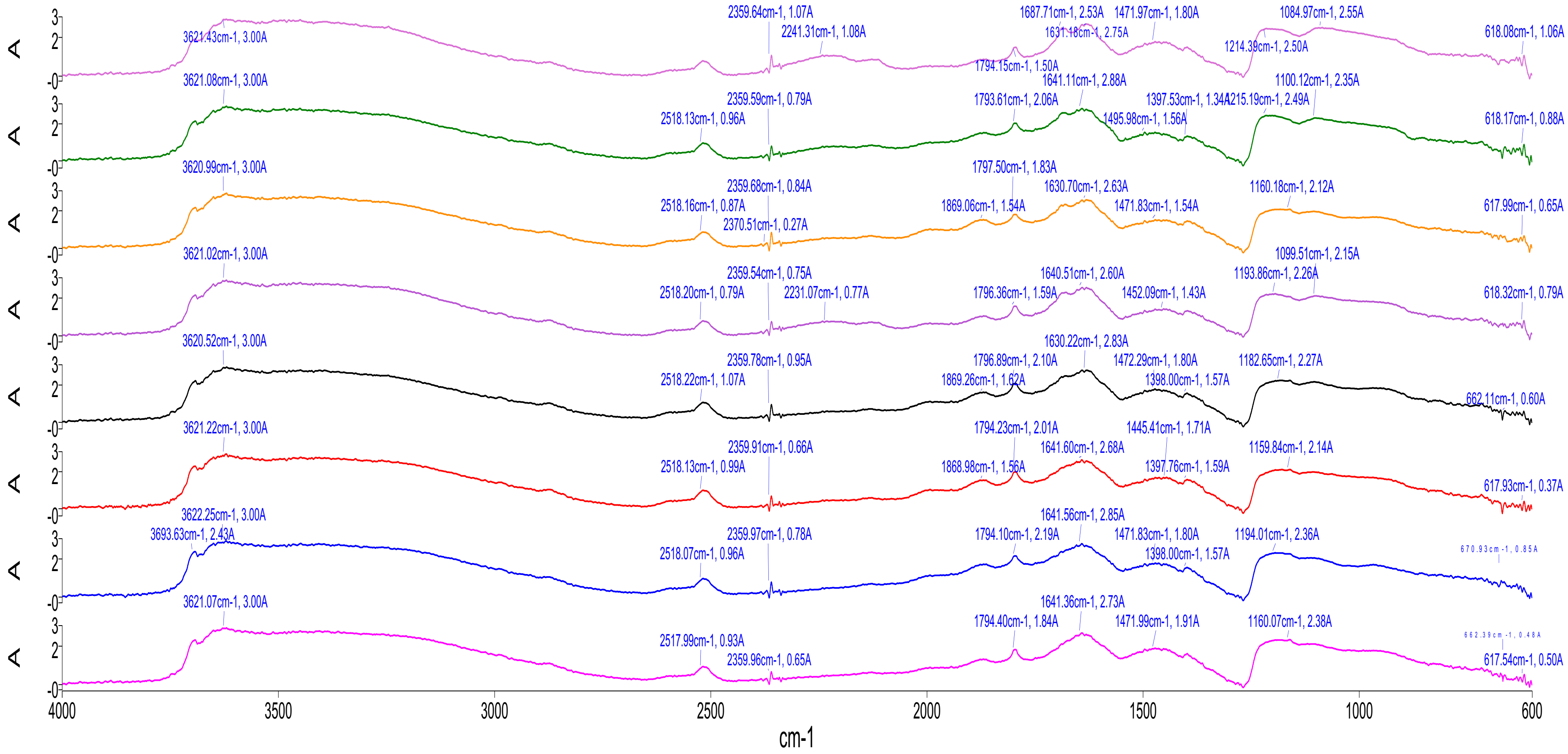
Çatalhöyük mudbrick (unit 21134, feature 255 Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (red and yellow); break-edge (green and orange) 1mm depth (navy and green); 5mm depth (purple and grey).

U21513_s4



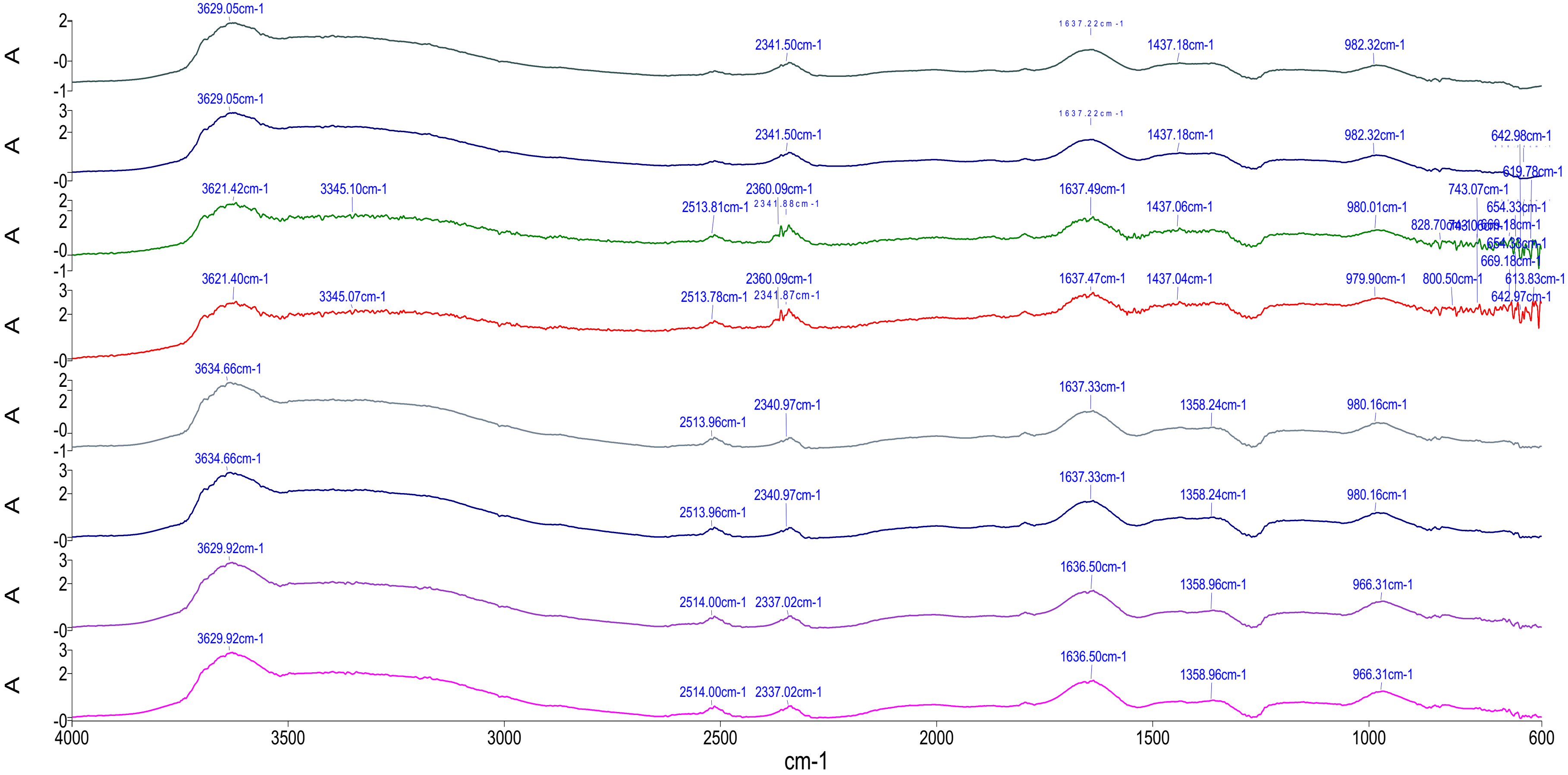
Çatalhöyük mudbrick (unit 21513, feature 1020, Building 113, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U21513_s5



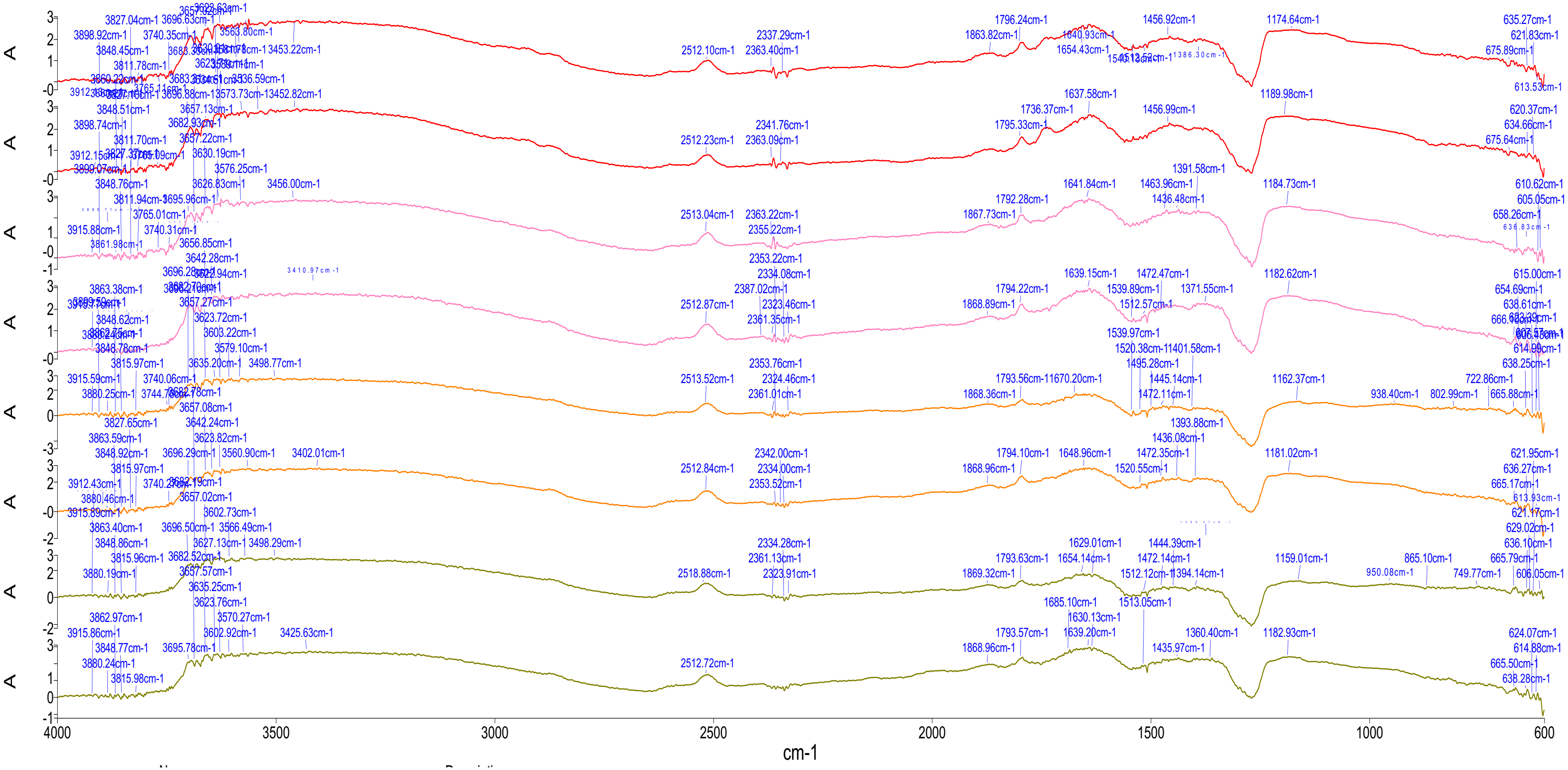
Çatalhöyük mudbrick (unit 21513, feature 1020, Building 113, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U22157_s1



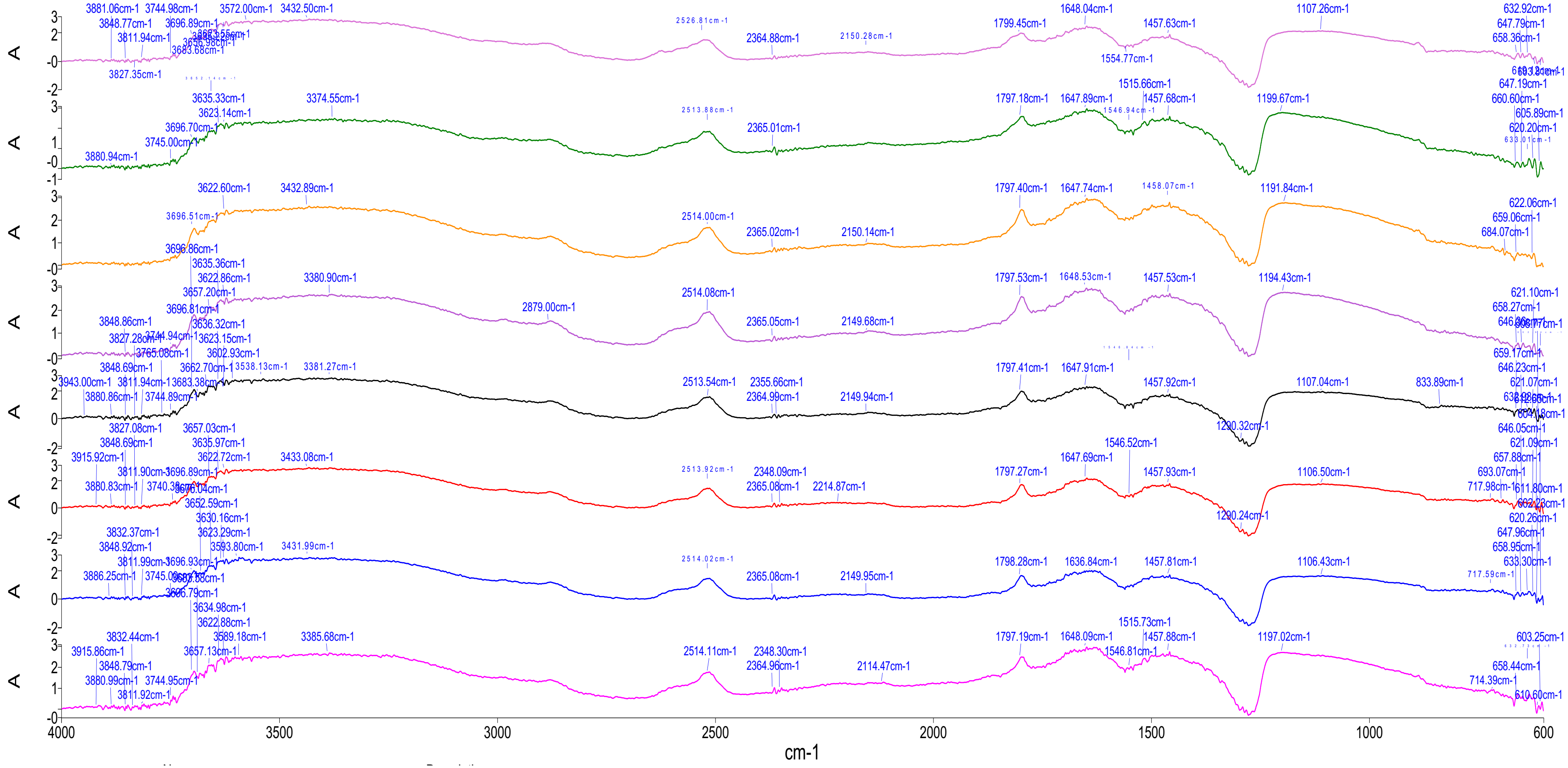
Çatalhöyük mudbrick (unit 22157, feature 229, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (grey and navy); break-edge (green and red) 1mm depth (grey and navy); 5mm depth (purple and pink).

U22159_s1



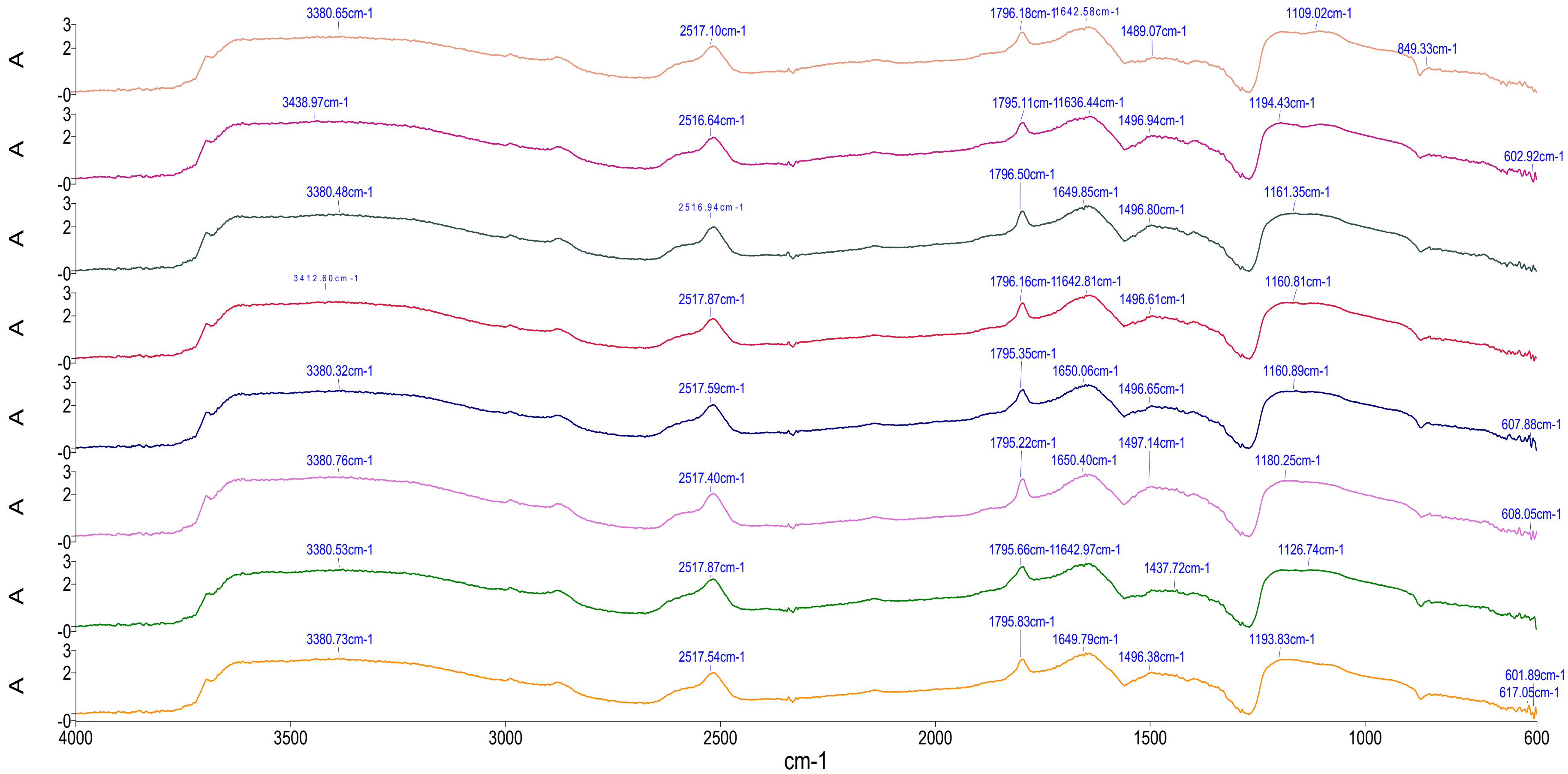
Çatalhöyük mudbrick (unit 22159, feature 231, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (red); break-edge (pink) 1mm depth (orange); 5mm depth (green).

U22341_s1



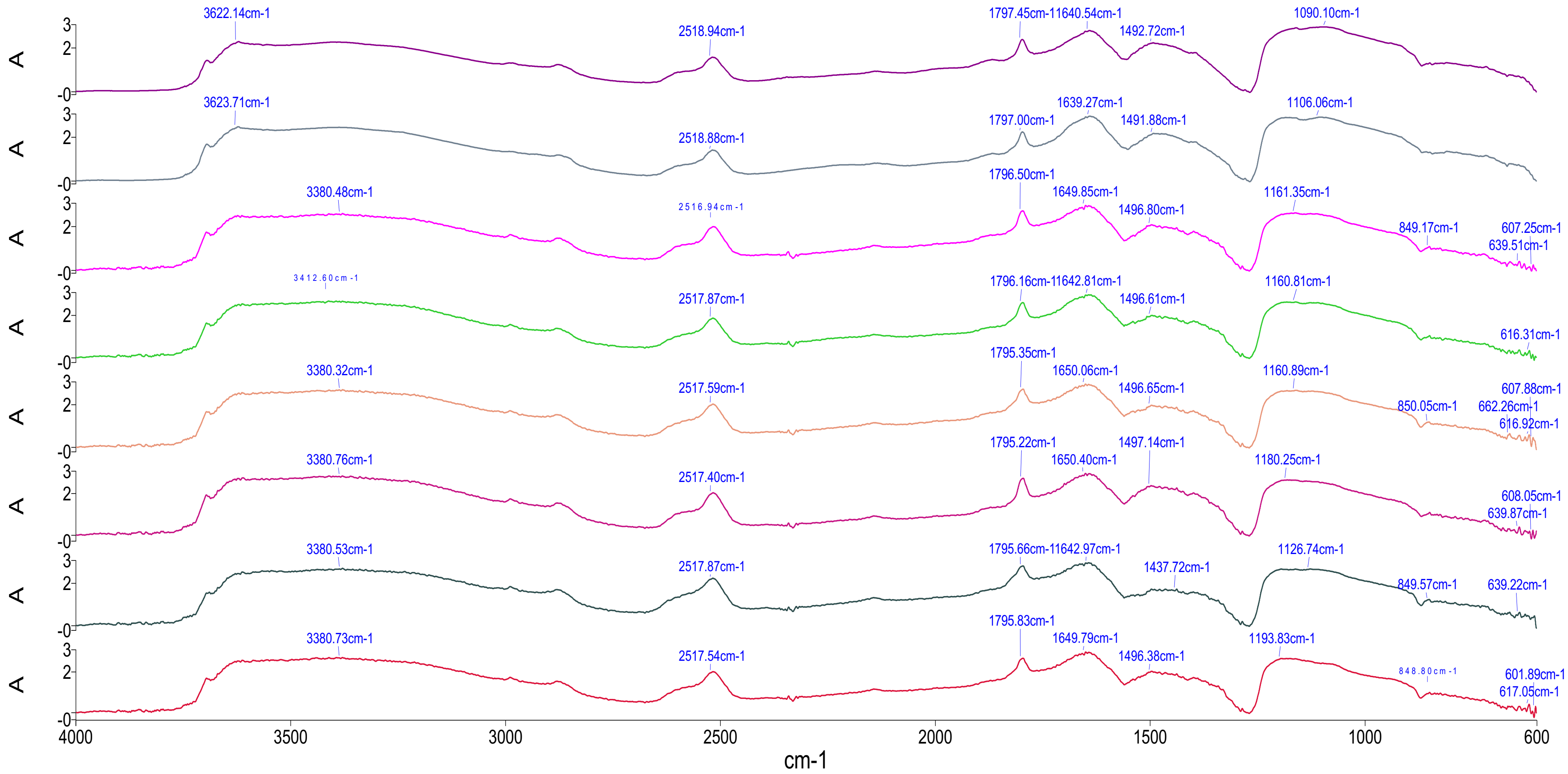
Çatalhöyük mudbrick (unit 22341, feature 3482, Building 89, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U22904_s1



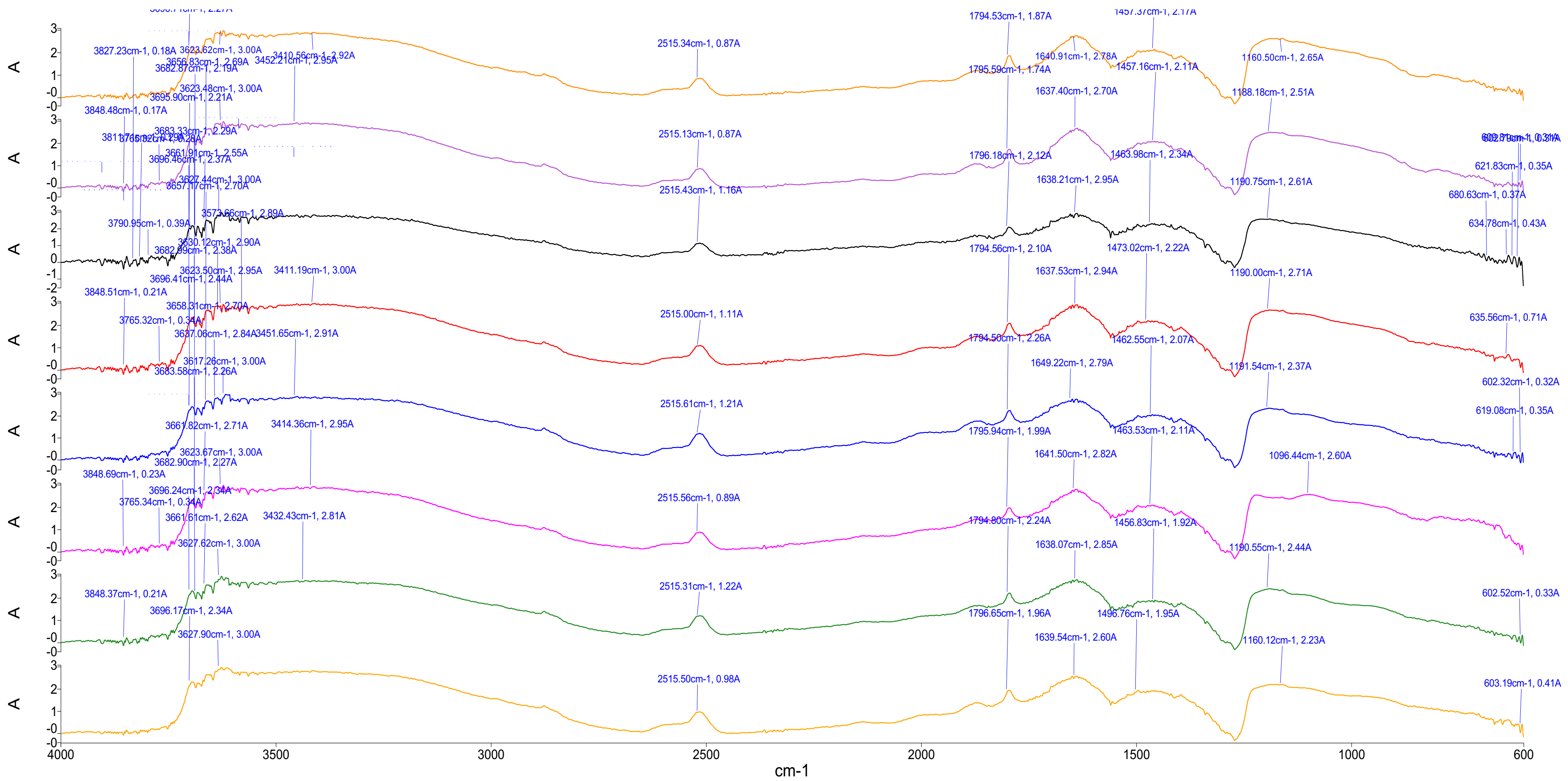
Çatalhöyük mudbrick (unit 22904, feature 4090, Building 96, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (peach and raspberry); break-edge (grey and red) 1mm depth (navy and pink); 5mm depth (green and yellow).

U22904_s2



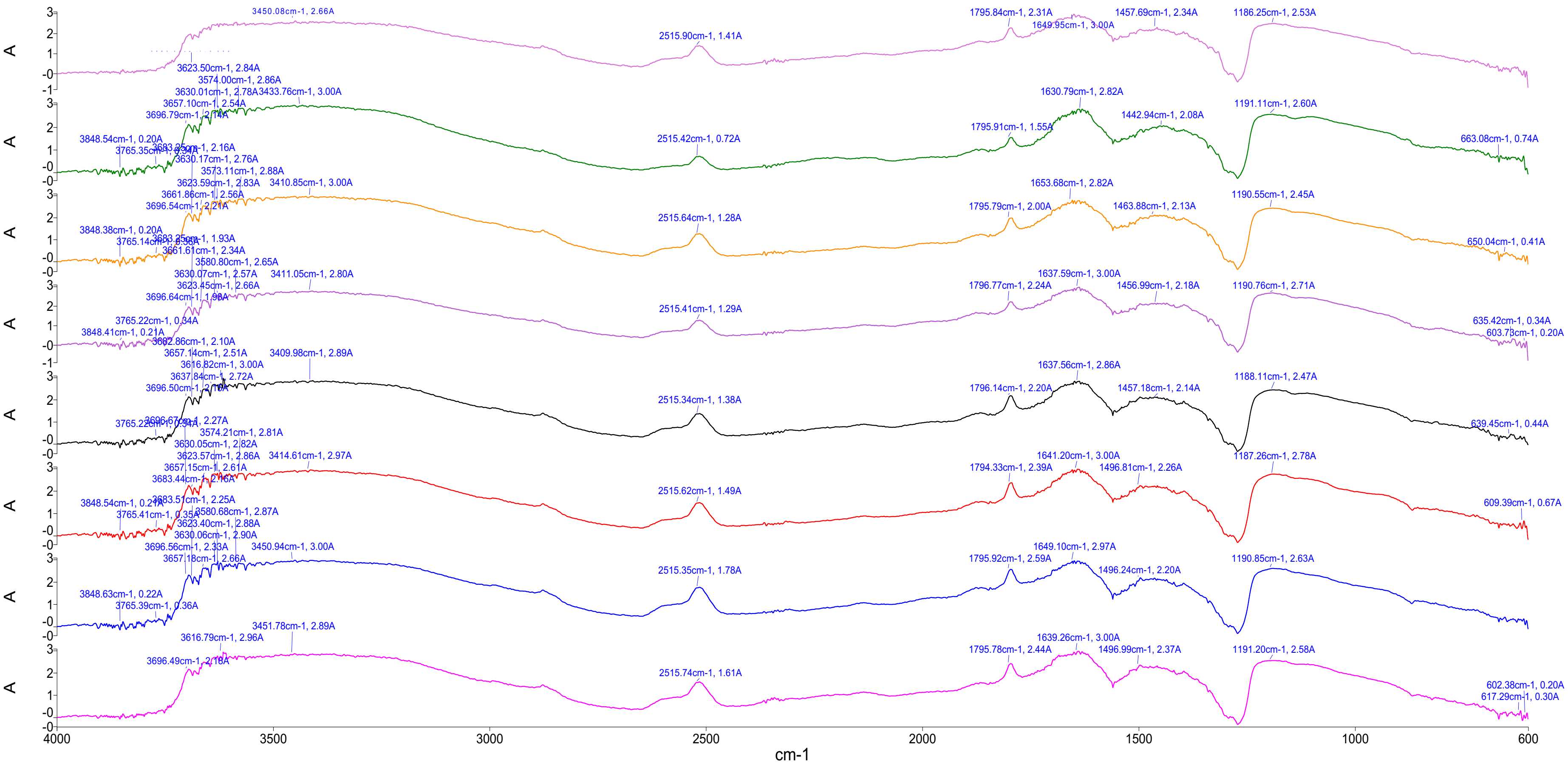
Çatalhöyük mudbrick (unit 22904, feature 4090, Building 96, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (burgundy and grey); break-edge (pink and green) 1mm depth (peach and raspberry); 5mm depth (grey and red).

U22922_s1



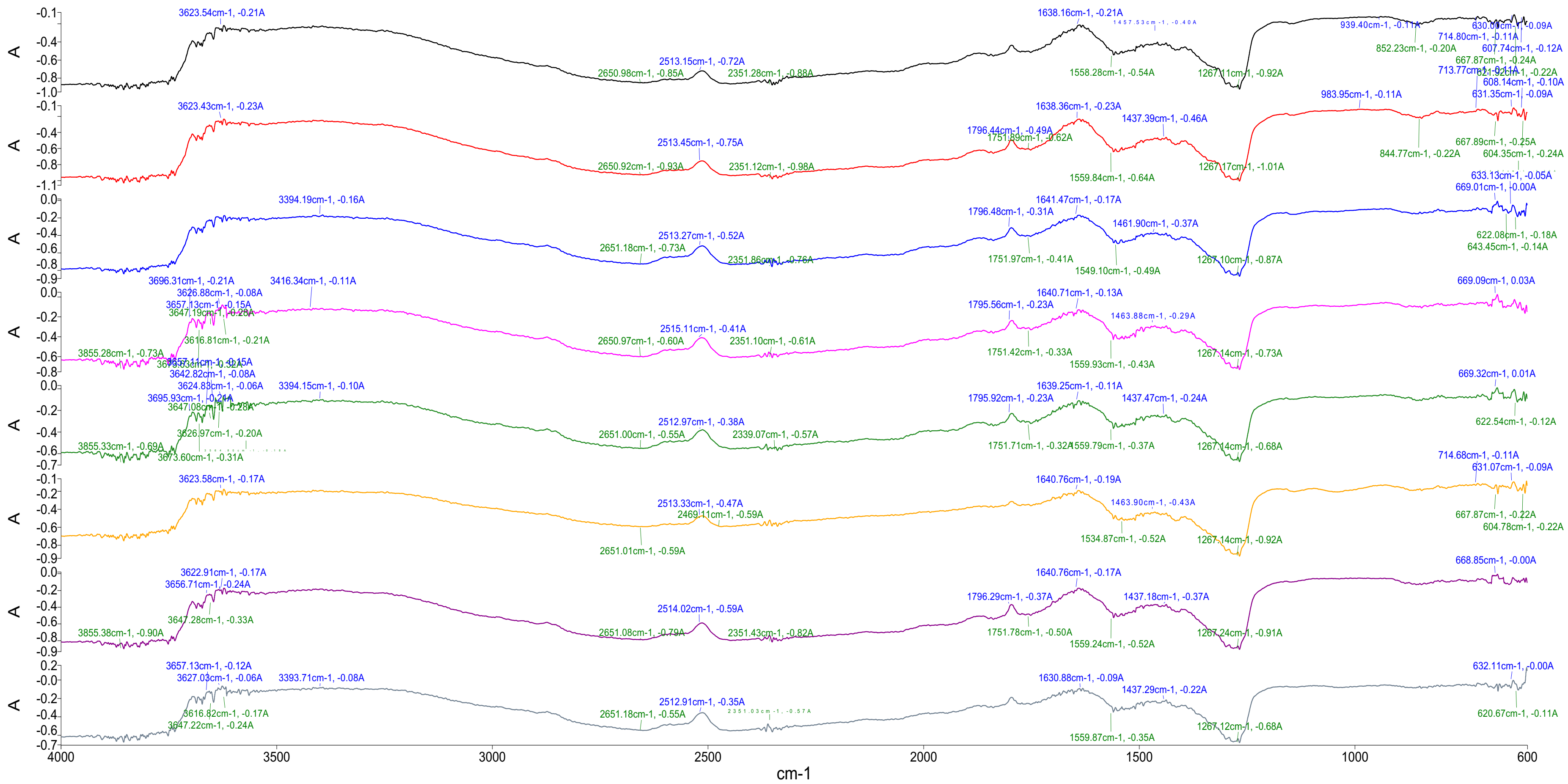
Çatalhöyük mudbrick (unit 22922, feature 3703, Building 104, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (orange and purple); break-edge (black and red) 1mm depth (navy and pink); 5mm depth (green and yellow).

U2866_s4



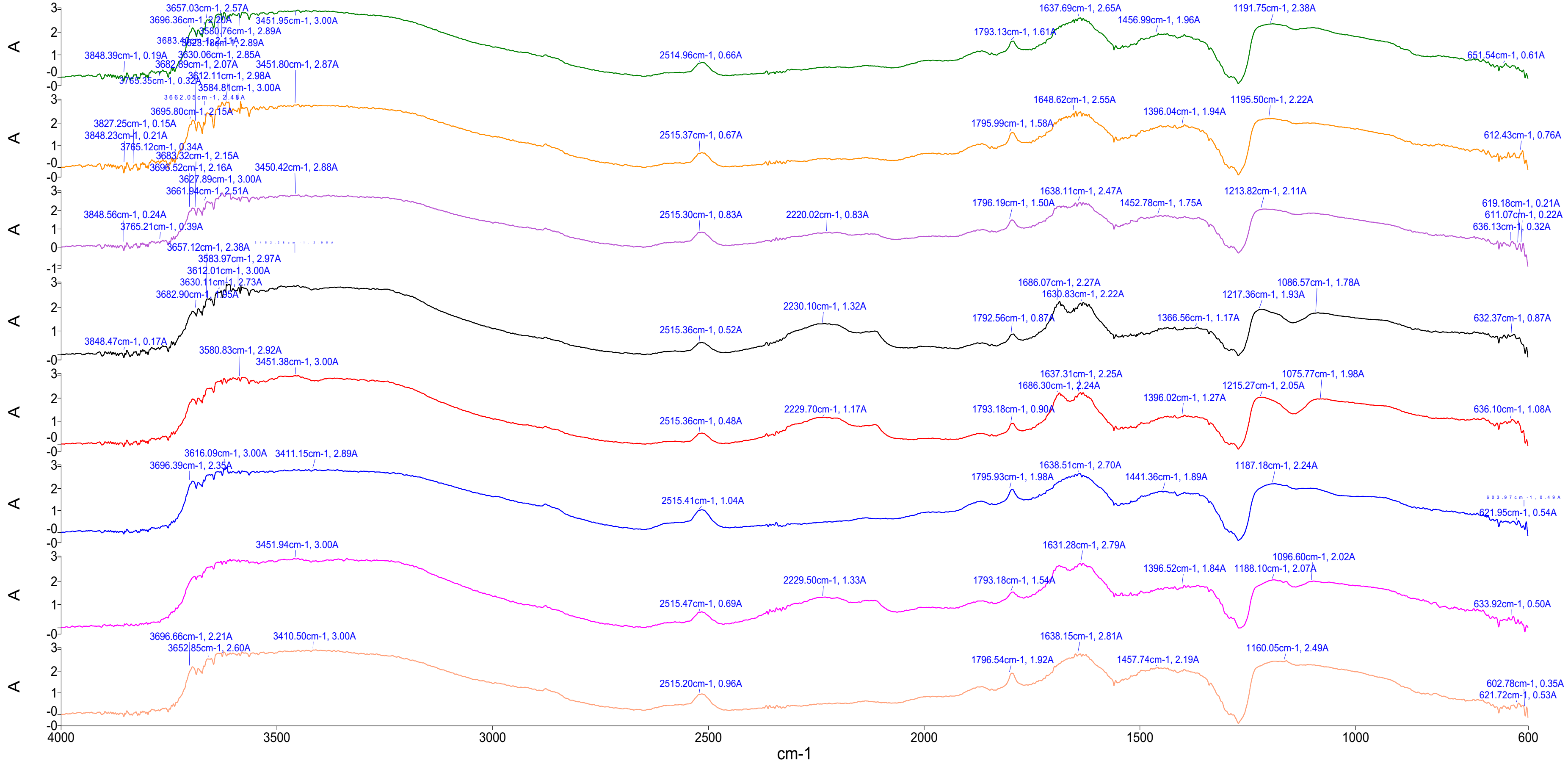
Çatalhöyük mudbrick (unit 2866, feature 88, Building 4, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (peach and burgundy); break-edge (grey and red) 1mm depth (navy and pink); 5mm depth (green and yellow).

U30352_s2



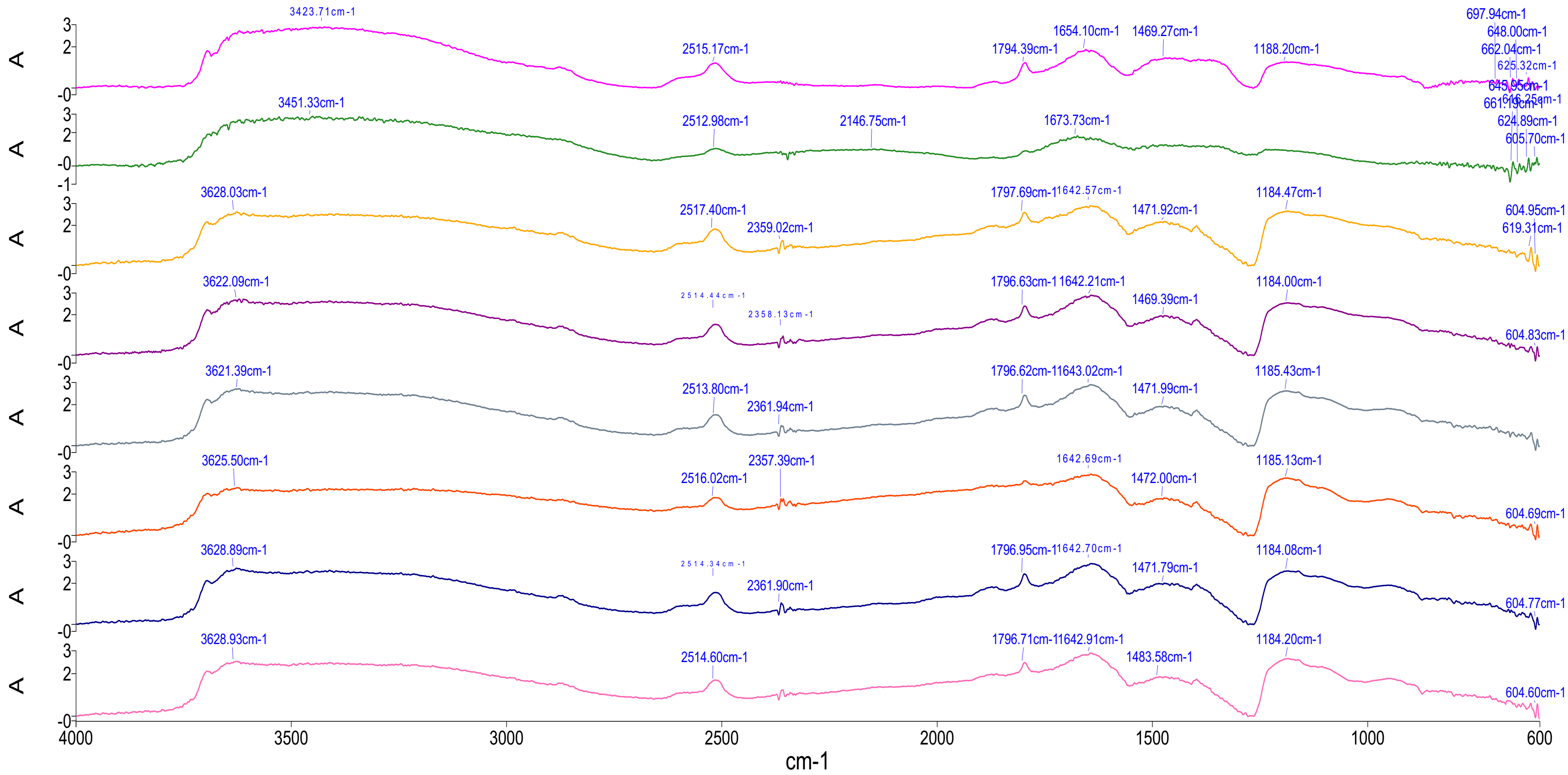
Çatalhöyük mudbrick (unit 30352, feature 263, Building 4, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (black and red); break-edge (blue and pink) 1mm depth (green and yellow); 5mm depth (purple and grey).

U3581_s3



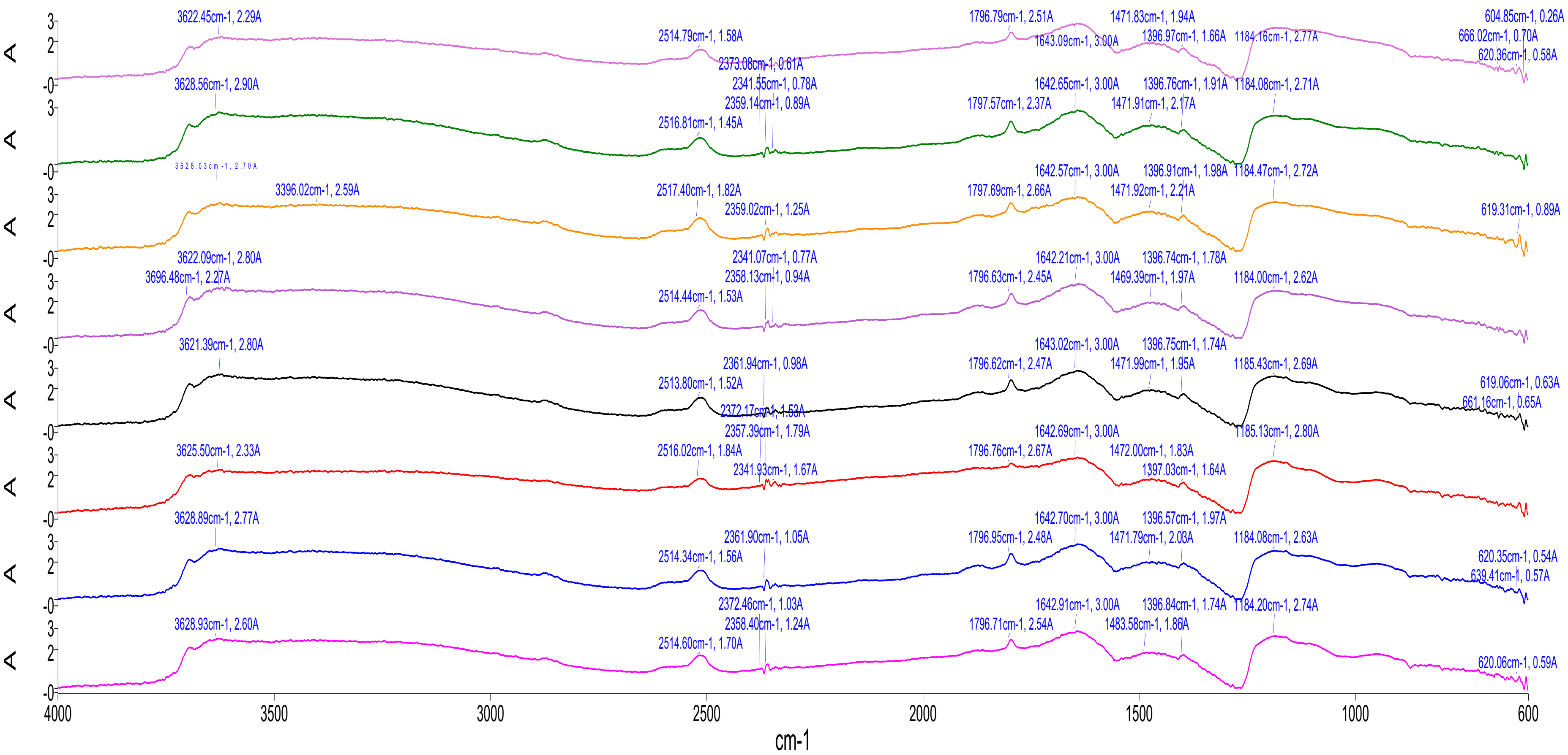
Çatalhöyük mudbrick (unit 3581, feature 163, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (green and yellow); break-edge (purple and black) 1mm depth (red and blue); 5mm depth (pink and peach).

U3864_s4



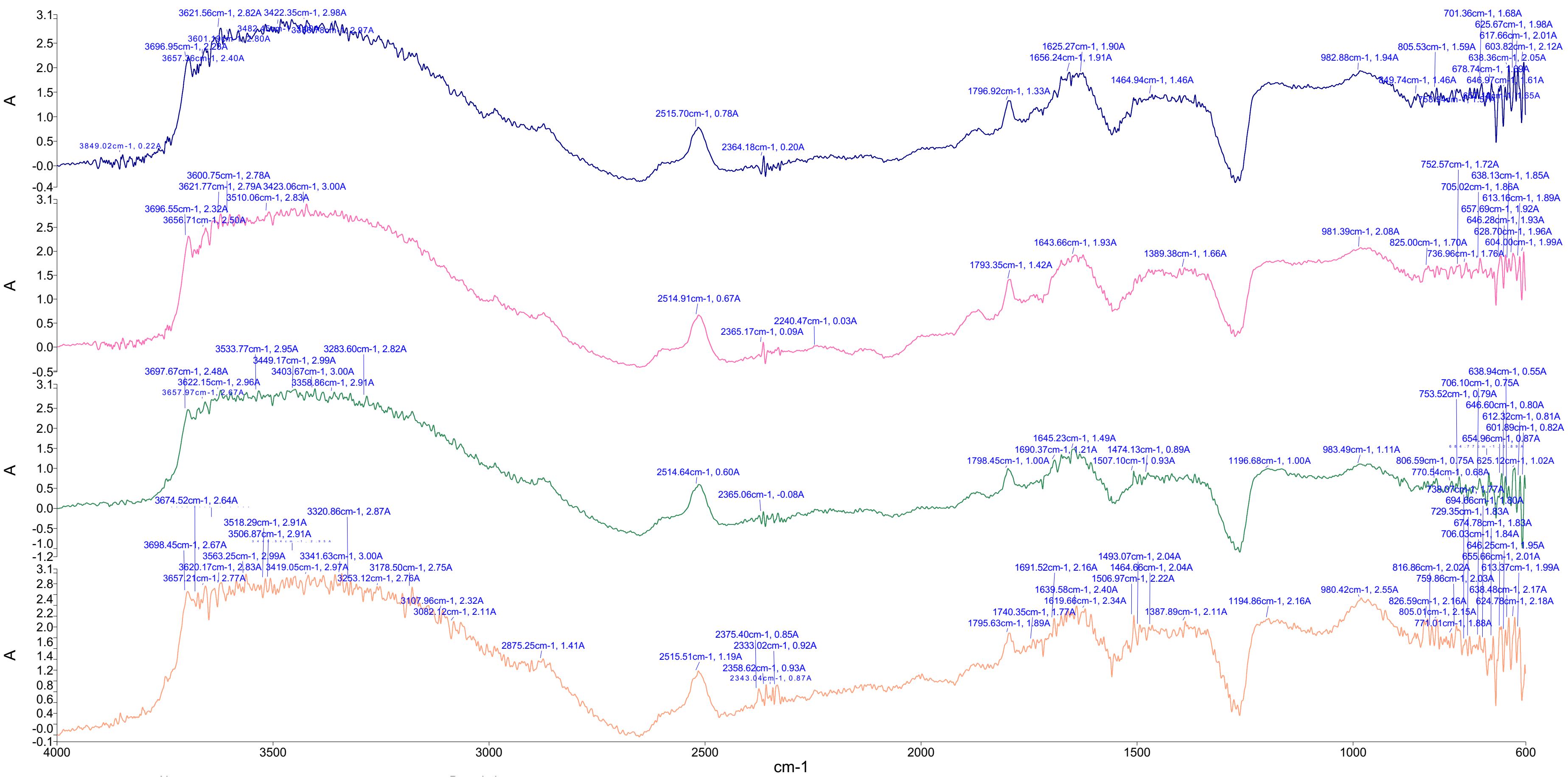
Çatalhöyük mudbrick (unit 3864, feature 229, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (yellow and burgundy) 1mm depth (grey and orange); 5mm depth (navy and pink).

U3864_s5



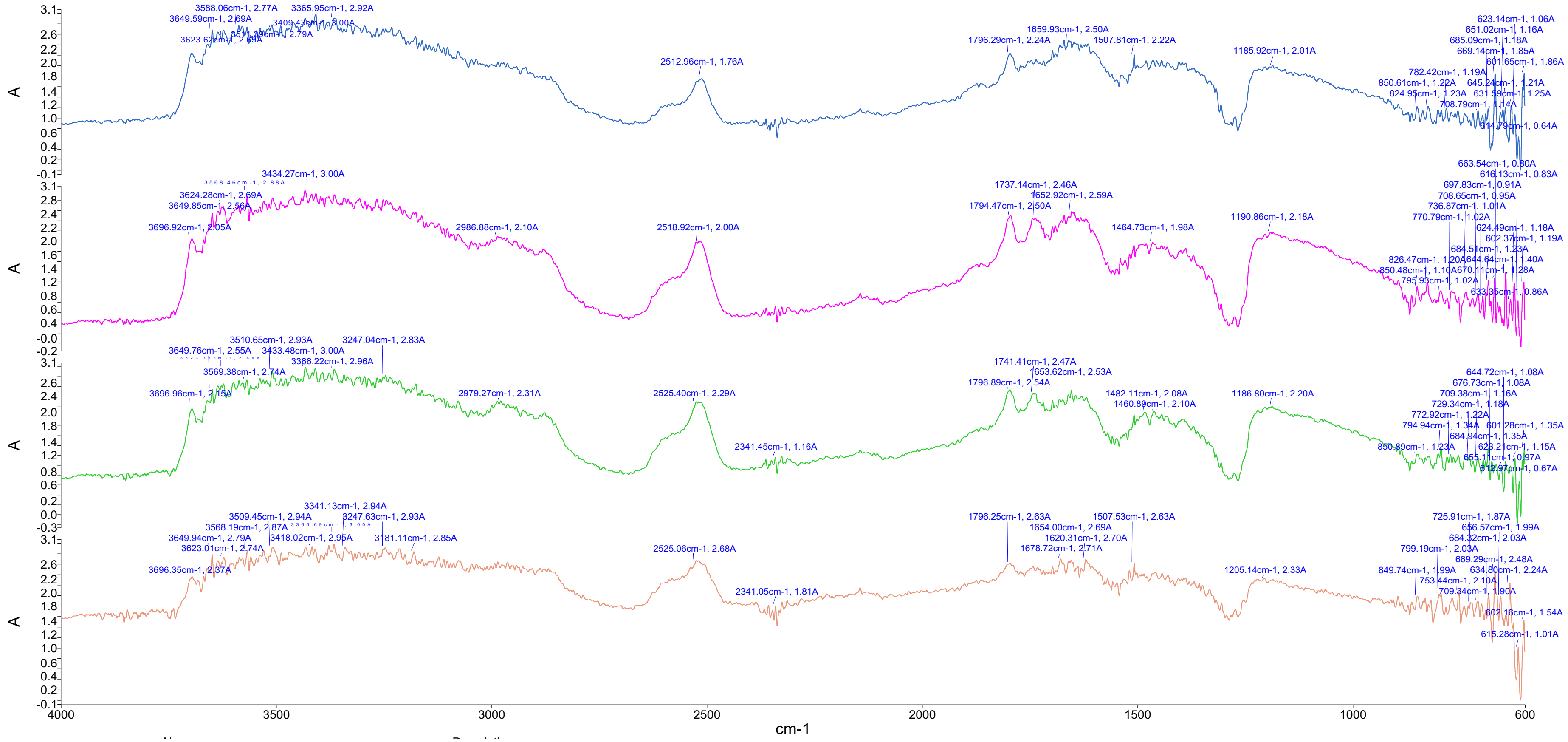
Çatalhöyük mudbrick (unit 3864, feature 229, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and fuchsia).

U3866_s3



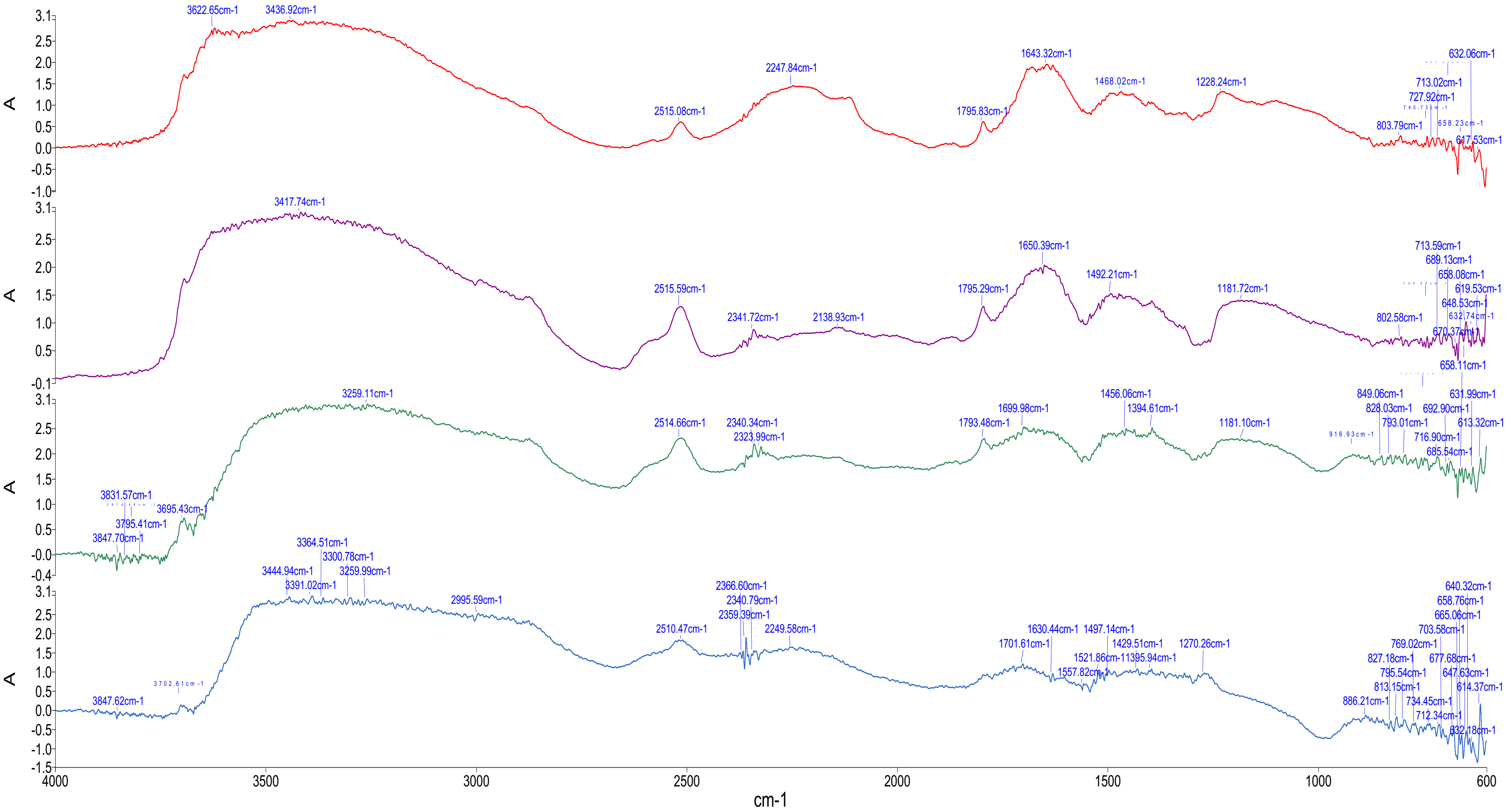
Çatalhöyük mudbrick (unit 3866, feature 230, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. One scan per location in descending order: surface (navy); break-edge (pink) 1mm depth (green); 5mm depth (orange).

U3866_s4



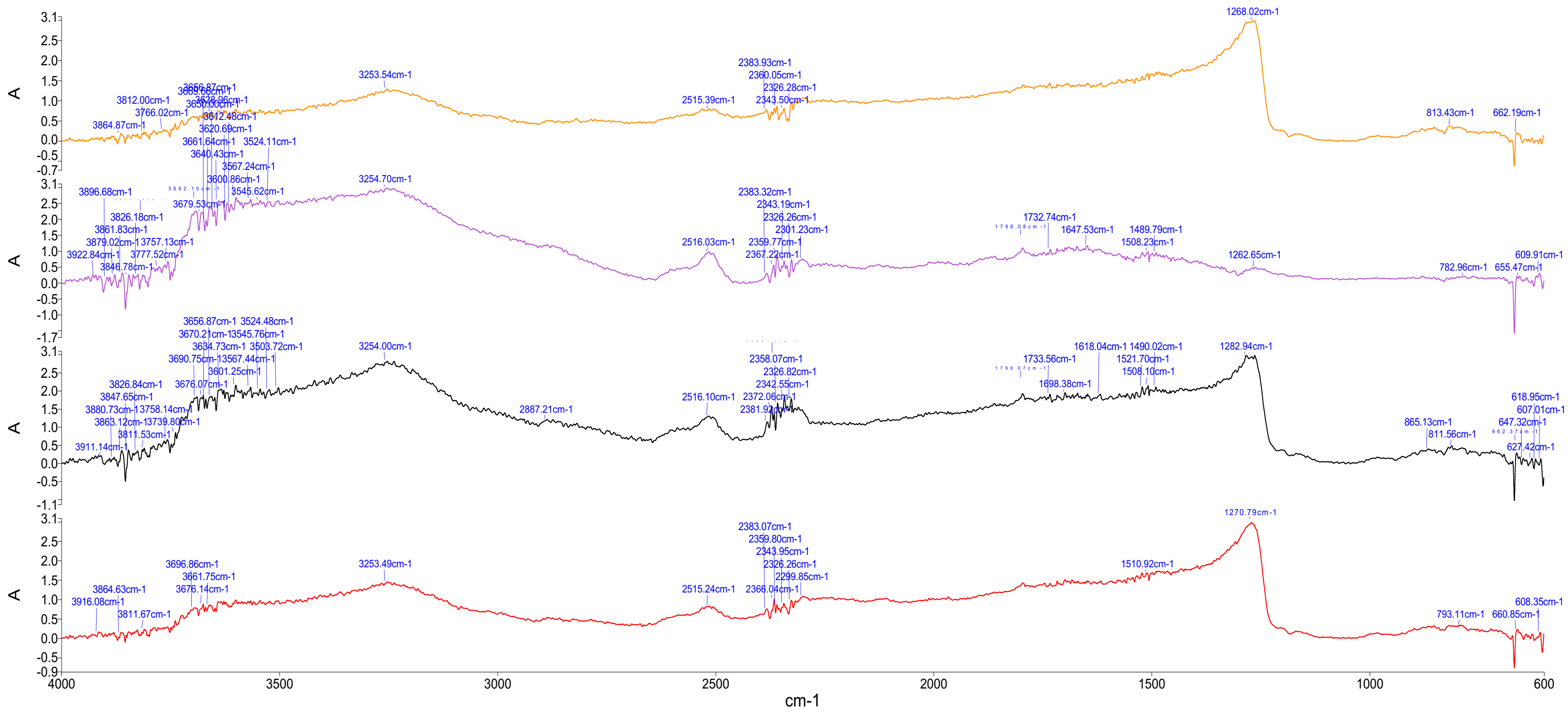
Çatalhöyük mudbrick (unit 3866, feature 230, Building 5, North Area) cross-section analysis, spectra collected by FTIR Multiscope. One scan per location in descending order: surface (blue); break-edge (pink) 1mm depth (green); 5mm depth (orange).

U4434_s4



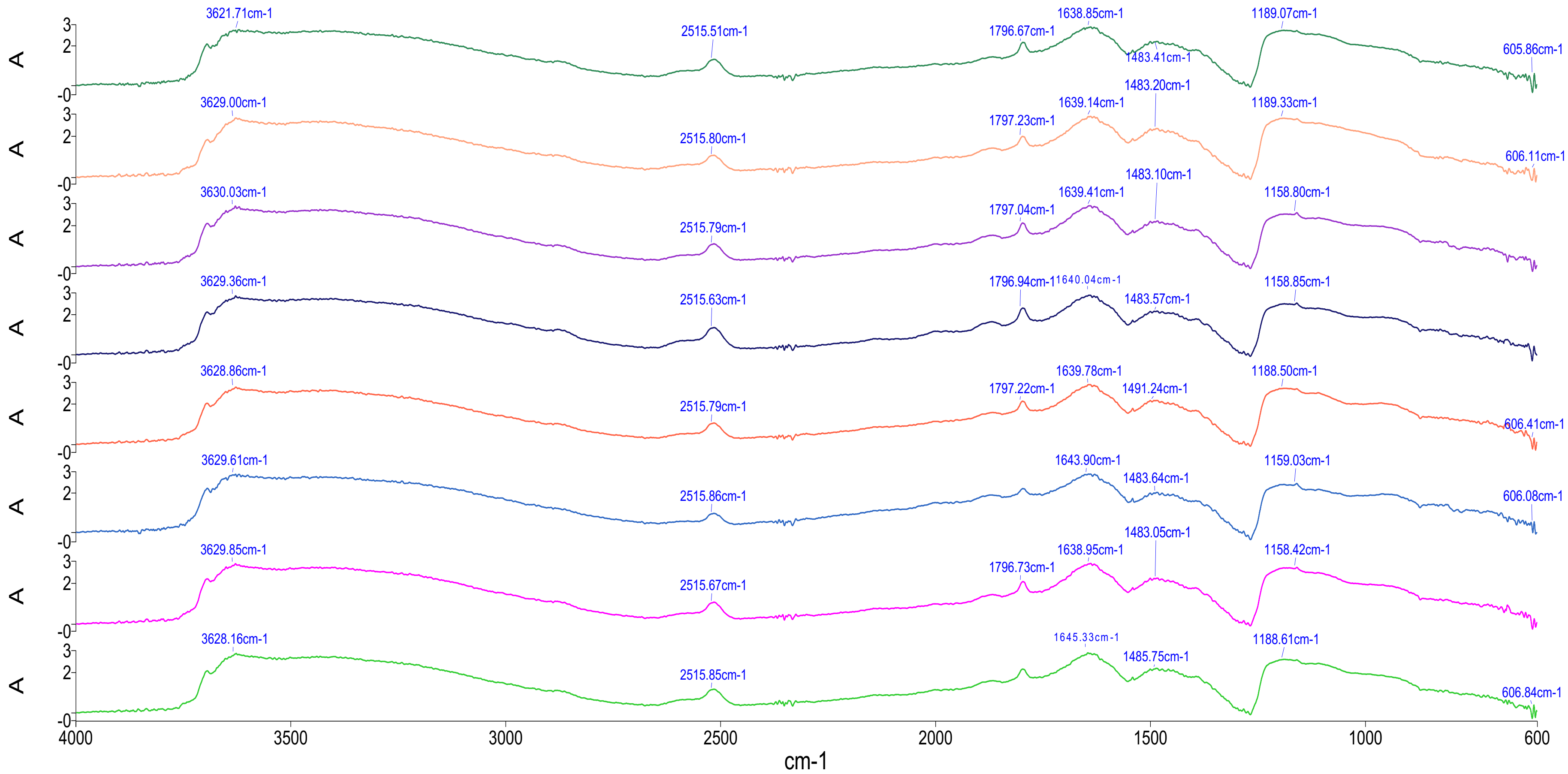
Çatalhöyük mudbrick (unit 3866, feature 483, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. One scan per location in descending order: surface (red); break-edge (burgundy) 1mm depth (green); 5mm depth (blue).

U4434_s5



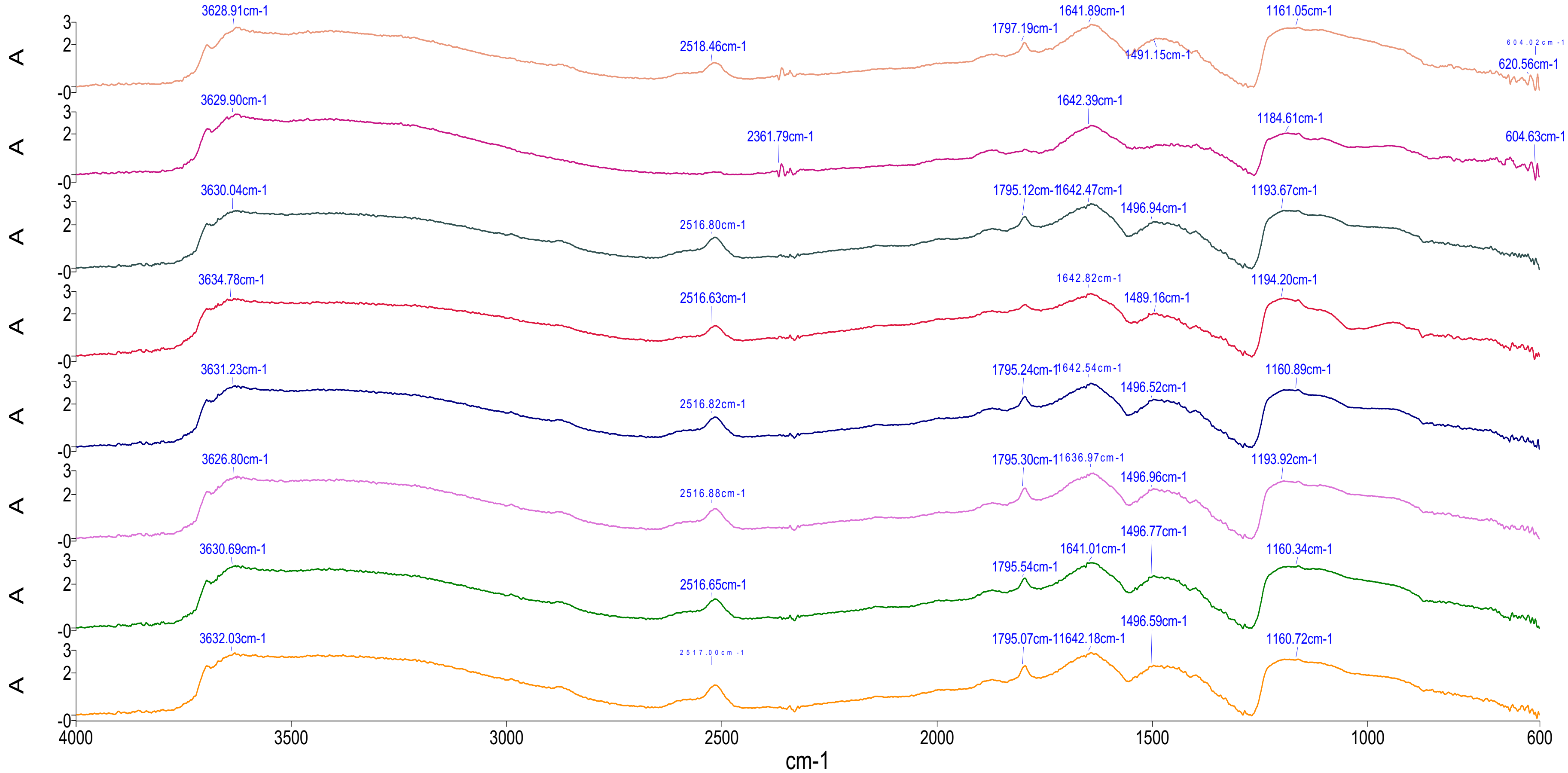
Çatalhöyük mudbrick (unit 3866, feature 483, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. One scan per location in descending order: surface (orange); break-edge (purple.) 1mm depth (black); 5mm depth (red).

U4550_s4



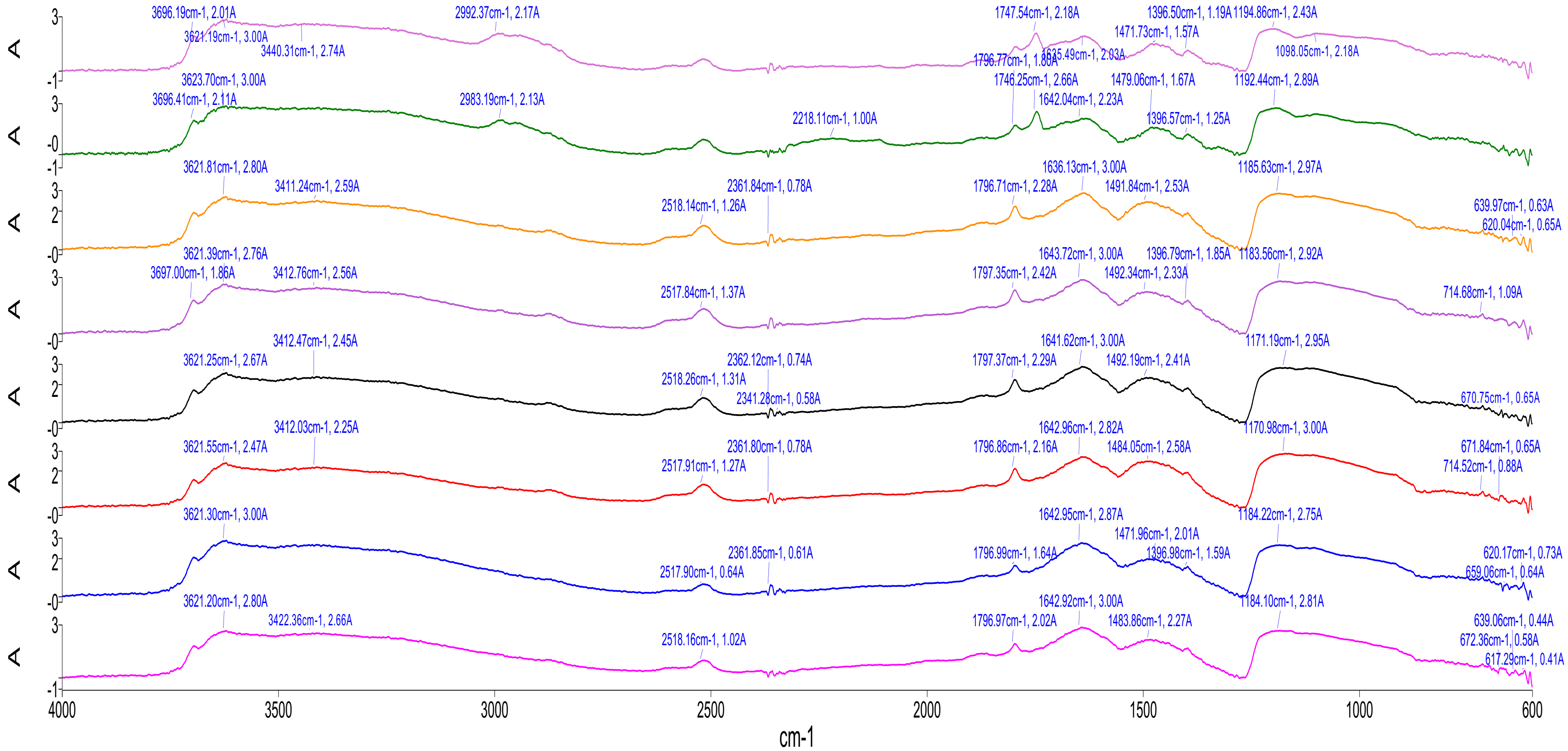
Çatalhöyük mudbrick (unit 4550, feature 479, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (green and yellow); break-edge (purple and navy) 1mm depth (red and blue); 5mm depth (pink and green).

U4550_s5



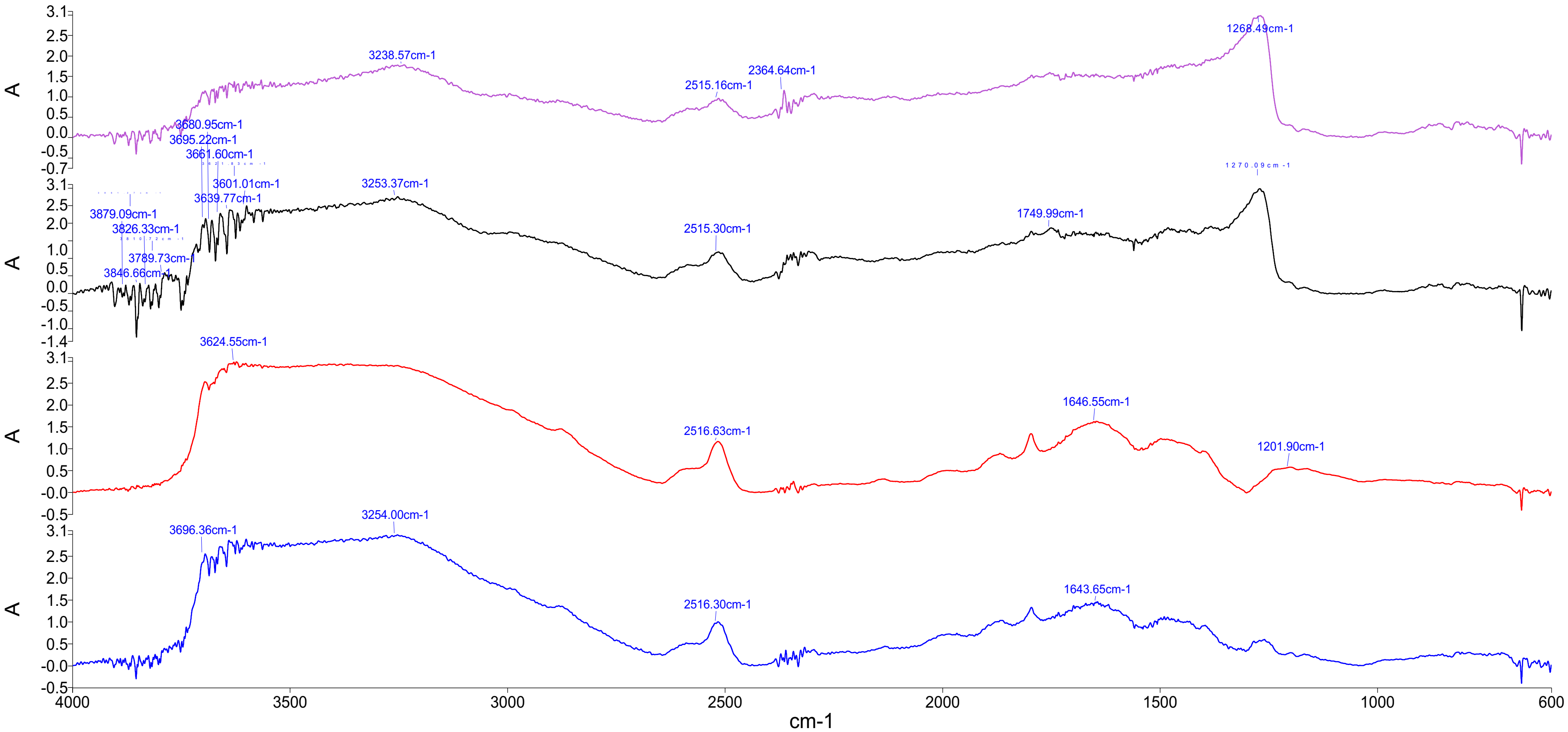
Çatalhöyük mudbrick (unit 4550, feature 479, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (orange and raspberry); break-edge (grey and red) 1mm depth (navy and pink); 5mm depth (green and orange).

U4607_s3



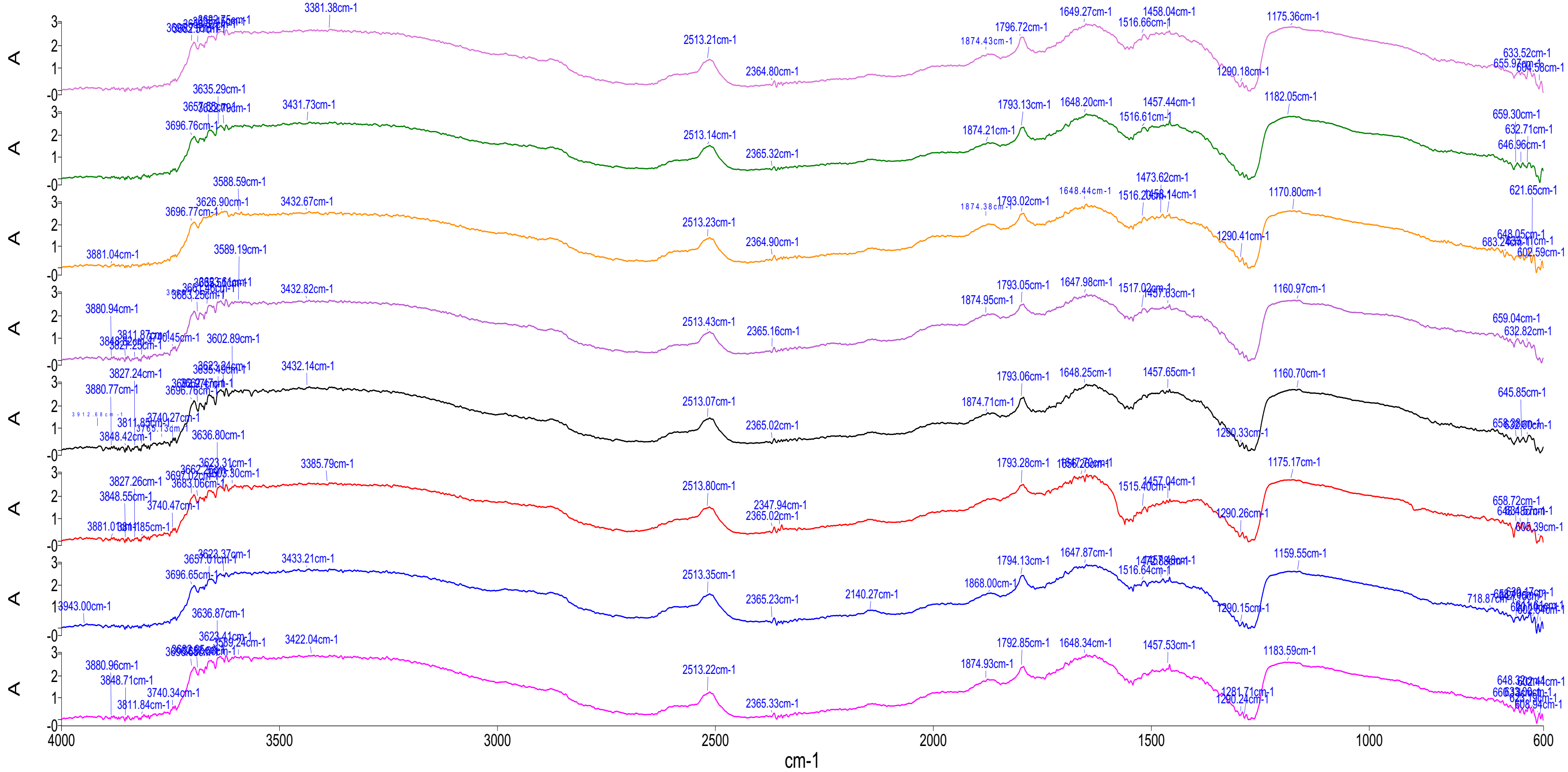
Çatalhöyük mudbrick (unit 4607, feature 484, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

U4607_s4



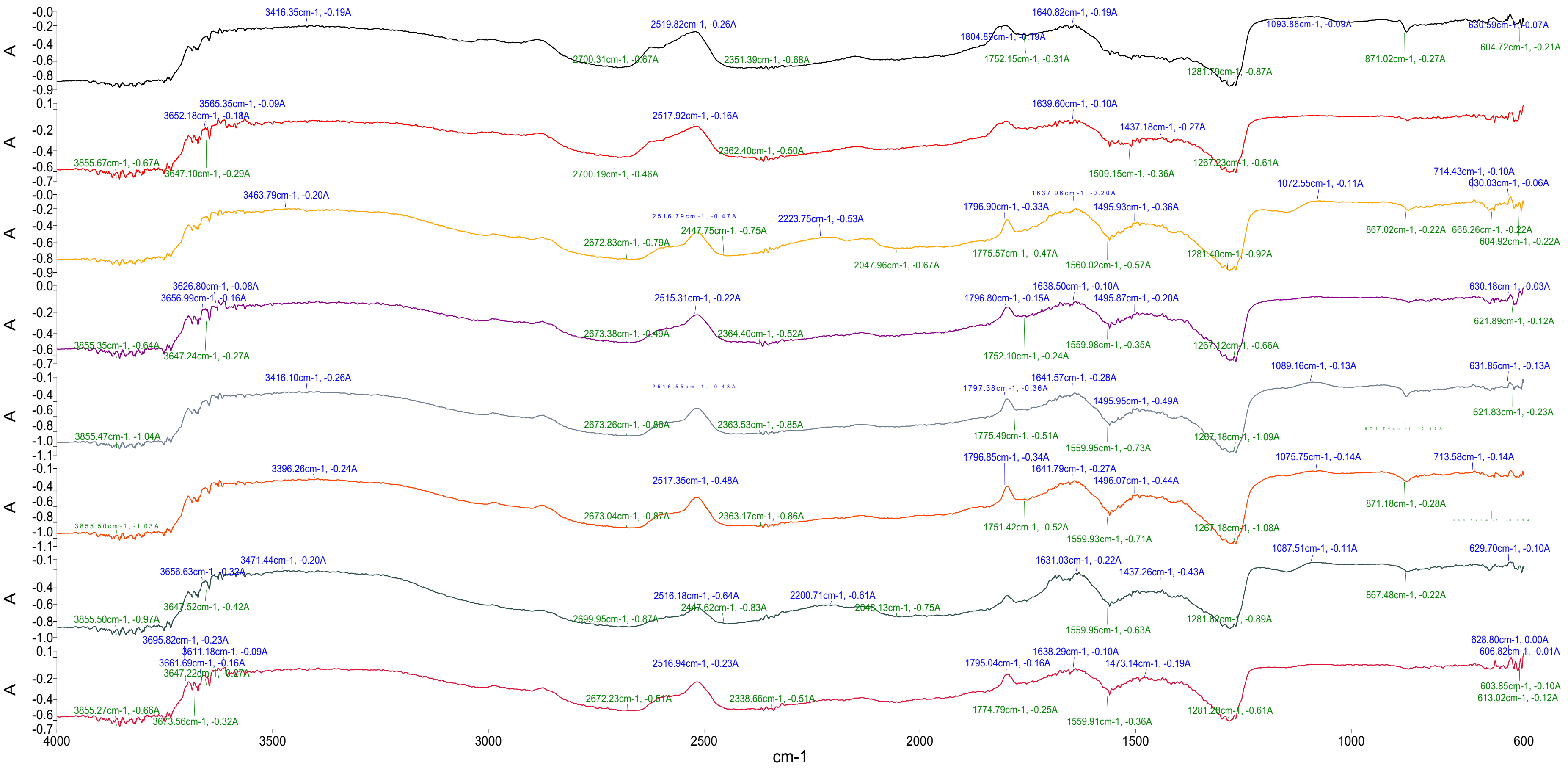
Çatalhöyük mudbrick (unit 4607, feature 484, Building 6, South Area) cross-section analysis, spectra collected by FTIR Multiscope. One scan per location in descending order: surface (purple); break-edge (black) 1mm depth (red); 5mm depth (blue).

U7975_s1



Çatalhöyük mudbrick (unit 7975, feature 1655, Building 49, North Area) cross-section analysis, spectra collected by FTIR Multiscope. Two scans per location in descending order: surface (pink and green); break-edge (orange and purple) 1mm depth (black and red); 5mm depth (blue and pink).

Consolidation Samples from 1996 Study



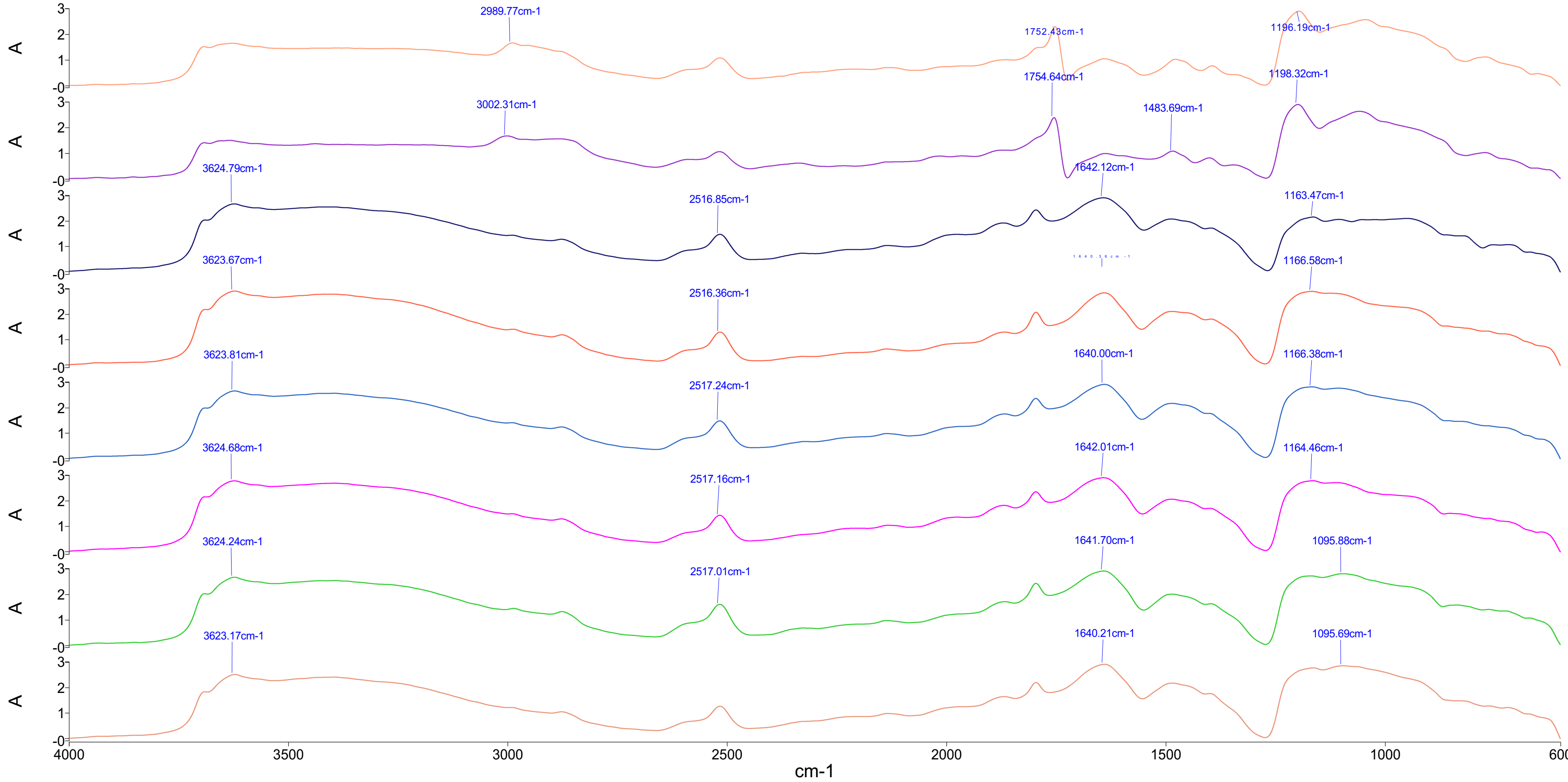
Spectra collected by FTIR Multiscope. Çatalhöyük 1996 consolidation test samples. Two scans per sample: sample 1 (black and red), sample 2 (yellow and purple), sample 3 (grey and 0range), sample 4 (navy and raspberry)

Unit	Sn°	Feature	Building	North/South	Material	FTIR	Energy	N° Scans	Consolidant Present	Records
1996 Matero	1				Plaster	X	100	2	Y not AC-33	PVAC
1996 Matero	2				Plaster	X	64	2	Y not AC-33	PVAC
1996 Matero	3				Plaster	X	140	2	Y not AC-33	PVAC
1996 Matero	4				Plaster	X	67-135	2	Y not AC-33	PVAC
U12321	4	1591	55	N	Mud Brick	X	170-240	8	N	Y
U12321	5	1591	52	N	Mud Brick	X	60-180	6	y	Y
U13694	14	1657	49	N	Mud Brick	X	120-140	8	N	N
U14160	3	2211	52	N	Mud Brick	X	55-122	8	N	Y
U1540	4	57	40	S	Mud Brick	X	55-75	4	N	N
U15838	5	6000		TPC	Mud Brick	X	60-90	8	Y	Y
U16368	1	1591	55	N	Plaster	X	115-140	8	Y	Y
U16370	1	1591	55	N	Plaster	X	120-308	8	N	N
U17589	4	3095	77	N	Plaster	X	55-70	8	Y	PVAC
U17745	1	1614	82	N	Mud Brick	X	130-220	8	N	Y
U17745	2	1614	82	N	Mud Brick	X	170-260	8	N	N
U17749	1	1613	82	N	Plaster	X	170-280	8	N	N
U17750	1	1617	82	N	Plaster	X	60-80	8	Y	Y
U17753	1	1615	82	N	Plaster	X	200-315	8	Y	Y
U17994	1	5013	79	S	Plaster	X	85	8	N	Y
U18570	1	5013	79	S	Plaster	X	220-295	8	Y	Y
U18670	1	4086	97	S	Composite	X	130-230	8	N	N
U18670	2	4086	97	S	Composite	X	160-300	8	N	N
U20568	4	1024	114	N	Plaster	X	220-290	8	Y	Y

U20589	1	297		S	Plaster	X	170-260	8	N	N
U20590	1	294		S	Mud Brick	X	120-140	8	N	N
U20591	1	97	4	S	Mud Brick	X	130-230	8	N	N
U20592	1	2015	52	N	Plaster	X	65-115	8	N	Y
U20593	1	2138	54	N	Mud Brick	X	170-220	8	N	N
U20594	1	3682	114	N	Mud Brick	X	220-290	8	N	N
U20595	1	1577	51	N	Mud Brick	X	210-260	8	N	Y
U21134	15	255	5	N	Mud Brick	X	55-70	2	N	N
U21334	14	255	5	N	Mud Brick	X	55-70	4	N	N
U21513	4	1022	113	N	composite	X	205-250	8	N	N
U21513	5	1022	113	N	Mud Brick	X	220-250	8	N	N
U22157	1	229	5	N	Plaster	X	65-115	4	N	N
U22158	1	230	5	N	Mud Brick	X	60-80	4	Y	Y
U22158	2	230	5	N	Mud Brick	X	55-75	4	y	Y
U22159	1	231	5	N	Mud Brick	X	55-75	8	N	Y
U22339	1	3483	89	S	Plaster	X	100-160	8	Y	Y
U22341	1	3482	89	S	Plaster	X	60-70	8	N	Y
U22342	1	3515	96	S	Plaster	X	170-260	8	Y	N
U22904	1	4090	96	S	Plaster	X	75-150	8	N	N
U22904	2	4090	96	S	Plaster	X	240-280	9	N	Y
U22906	1	4088	97	S	Composite	X	115-140	8	Y	N
U22906	2	4088	97	S	Mud Brick	X	180-210	8	Y	Y
U22922	1	3703	104	S	Mud Brick	X	55-160	8	N	N
U2866	4	88	4	S	Mud Brick	X	60-130	8	N	N
U30352	2	263	4	S	Mud Brick	X	75-150	8	N	N
U3581	3	163	-	N	Mud Brick	X	75-140	8	N	N
U3864	4	229	5	N	Composite	X	55-75	4	N	N
U3864	5	229	5	N	Plaster	X	140-270	8	N	Y
U3866	3	230	5	N	Plaster	X	60-70	4	N	N

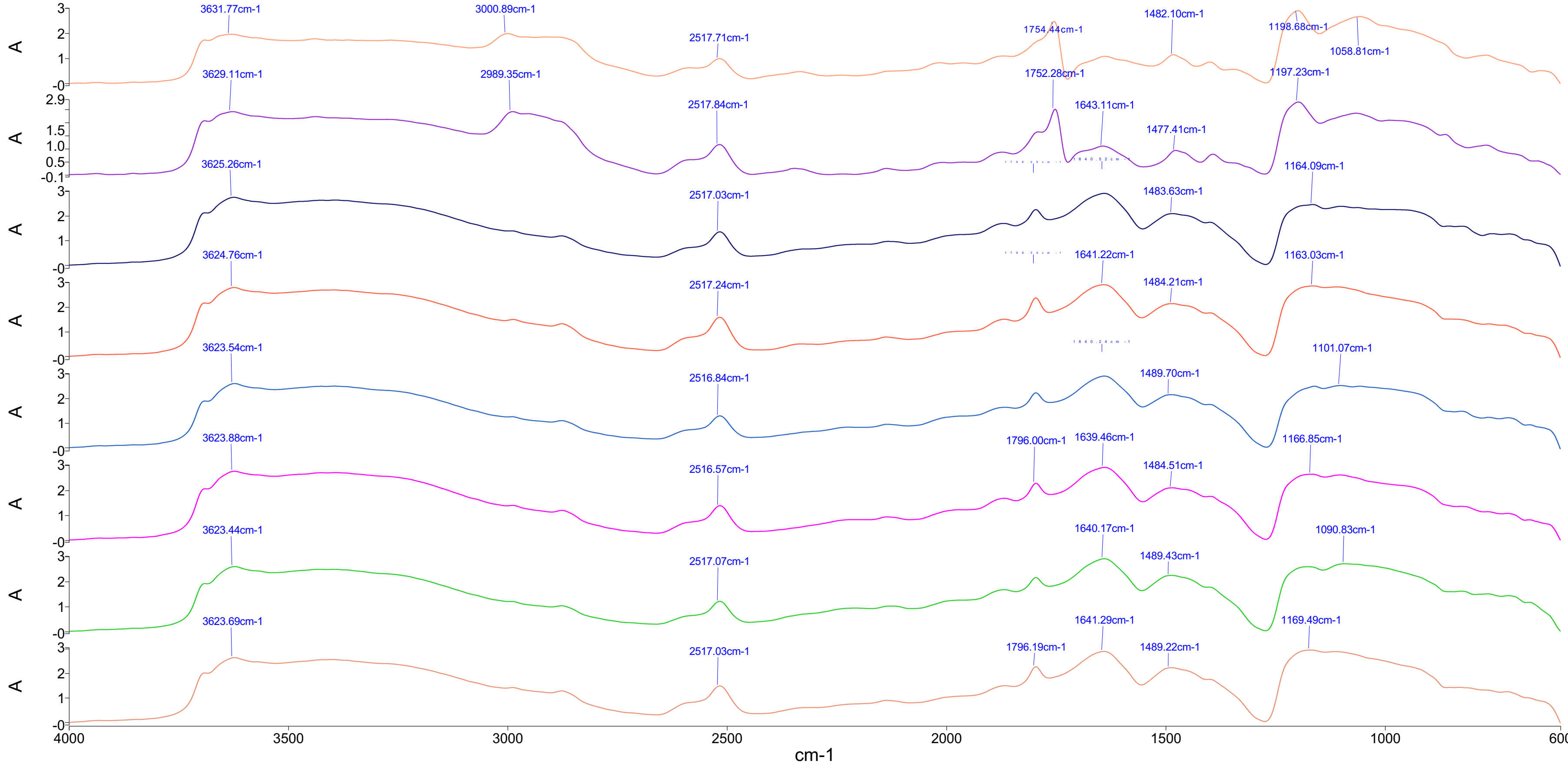
U3866	4	230	5	N	Plaster	X	55-75	4	Y	N
U4434	4	483	6	S	Mud Brick	X	60-70	4	N	N
U4434	5	483	6	S	Mud Brick	X	75-150	4	N	Y
U4550	4	479	6	S	Mud Brick	X	170-250	8	N	N
U4550	5	479	6	S	Plaster	X	170-230	8	N	Y
U4607	3	484	6	S	Plaster	X	55-75	3	N	N
U4607	4	484	6	S	Plaster	X	240-365	8	Y	Y
U7975	1	1655	49	N	Mud Brick	X	55-75	8	N	y

Parallel substrate testing
Sample 1



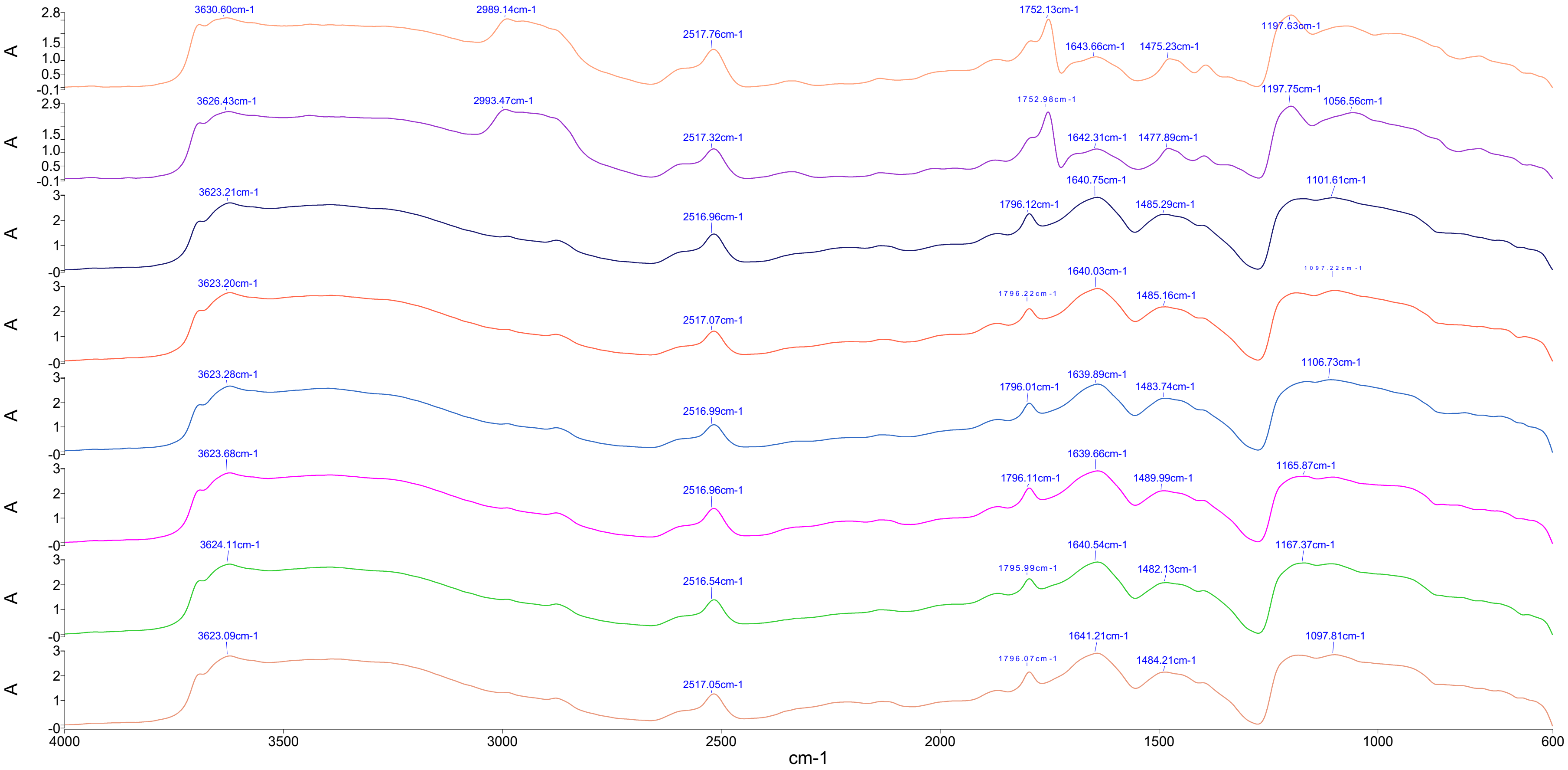
Spectra collected by FTIR Multiscope. Parallel substrate tests. Two scans per location in descending order: surface (peach and purple); break-edge (navy and orange) 1mm depth (blue and pink); 5mm depth (green and tan).

Parallel substrate testing
Sample 2



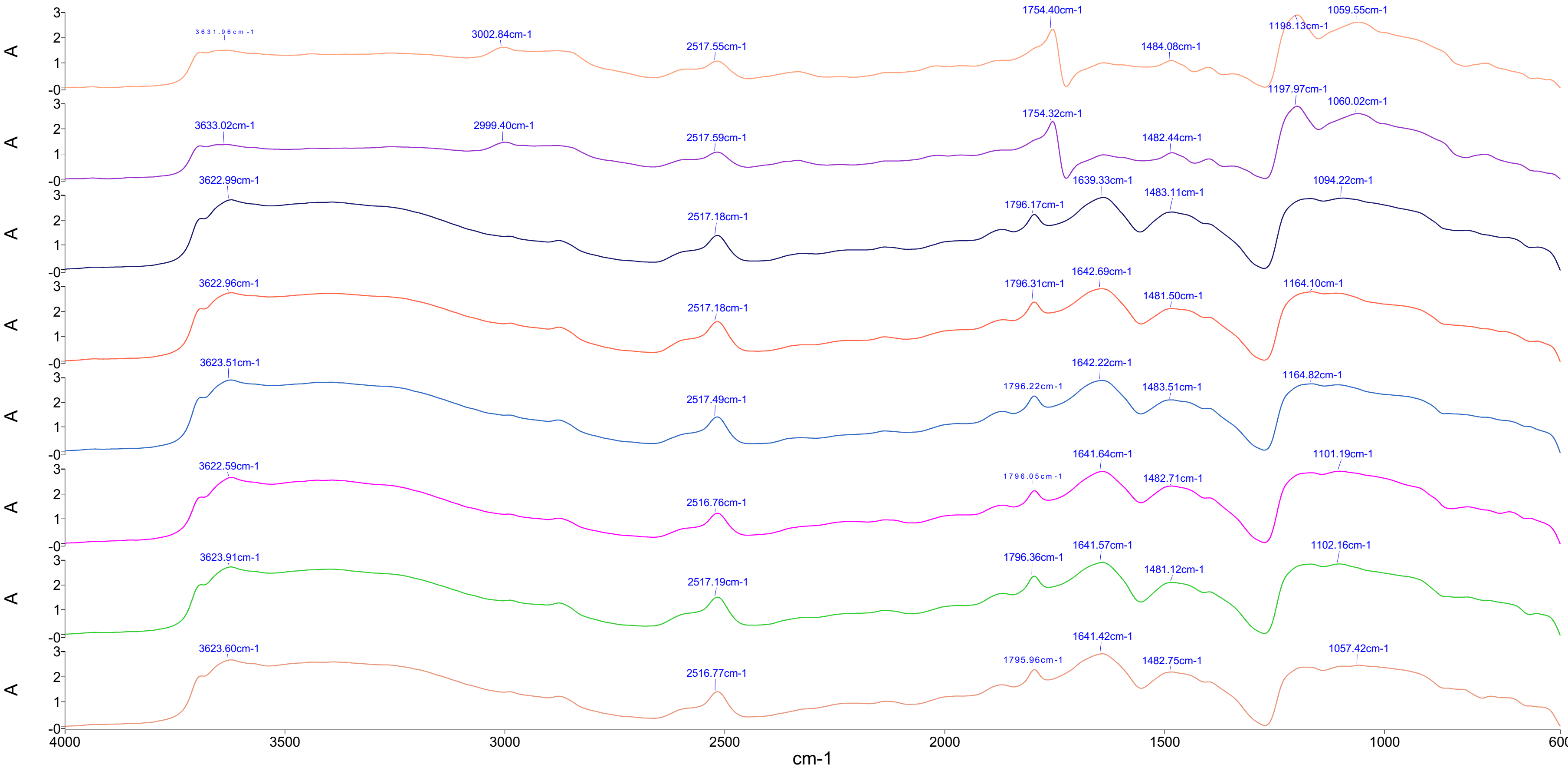
Spectra collected by FTIR Multiscope. Parallel substrate tests. Two scans per location in descending order: surface (peach and purple); break-edge (navy and orange) 1mm depth (blue and pink); 5mm depth (green and tan).

Parallel substrate testing
Sample 3



Spectra collected by FTIR Multiscope. Parallel substrate tests. Two scans per location in descending order: surface (peach and purple); break-edge (navy and orange) 1mm depth (blue and pink); 5mm depth (green and tan).

Parallel substrate testing
Sample 4



Spectra collected by FTIR Multiscope. Parallel substrate tests. Two scans per location in descending order: surface (peach and purple); break-edge (navy and orange) 1mm depth (blue and pink); 5mm depth (green and tan).