GEOLOGY AND JOINT ANALYSIS OF THE DERİNKUYU AND KAYMAKLI UNDERGROUND CITIES OF CAPPADOCIA, TURKEY

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MEHMET ÖZGÜR MUTLU

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JOINT ANALYSES IN THE UNDERGROUD CITIES OF CAPPADOCIA

submitted by **MEHMET ÖZGÜR MUTLU** in partial fulfillment of the equirements for the degree of **Master of Science in Geological Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Vedat Doyuran ________________
Head of Department, **Geological Engineering**

Prof. Dr. Vedat Toprak
Supervisor, **Geological Engineering Dept., METU** ________________

Assoc. Prof. Dr. Deniz Burcu Erciyas
Co-Supervisor, **City and Regional Planning Dept., METU** ________________

Examining Committee Members:

Prof. Dr. Asuman G. Türkmenoğlu ______________________
Geological Engineering Dept., METU

Prof. Dr. Vedat Toprak ______________________
Geological Engineering Dept., METU

Prof. Dr. Nurkan Karahanoğlu
Geological Engineering Dept., METU ______________________

Assoc. Prof. Dr. Bora Rojay
Geological Engineering Dept., METU ______________________

Dr. Arda Arcasoy
Arcasoy Consulting ______________________

Date:

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : Mehmet Özgür MUTLU

Signature :

ABSTRACT

GEOLOGY AND JOINT ANALYSES OF THE DERİNKUYU AND KAYMAKLI UNDERGROUND CITIES OF CAPPADOCIA, TURKEY

Mutlu, Mehmet Özgür

M. Sc., Department of Geological Engineering

Supervisor: Prof. Dr. Vedat Toprak

Co-Supervisor: Assoc. Prof. Dr. Deniz Burcu Erciyas

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This thesis attempts to detect the ignimbrite units in which the underground cities were carved and the relationship between the joints in these ignimbrites and the walls of underground cities. Orientation of rooms, directions of walls and joints are input data used in the study. Two sites in Cappadocia (Derinkuyu and Kaymaklı) are selected to investigate the relationship. Measurements taken from 46 rooms of Derinkuyu and 64 rooms of Kaymaklı are analyzed for the room and joint directions, joint locations in the room and joint densities. The density analyses are also performed in the field for Kızılkaya and Gördeles ignimbrites.

Conclusions derived from the analysis are: 1) Derinkuyu is carved within Kızılkaya and Kaymaklı is carved within Gördeles ignimbrite, 2) The thickness of Kızılkaya and Gördeles ignimbrites observed 13.5 and 34 m, respectively, in the field. The probable thickness of Derinkuyu and Kaymaklı underground cities are 40 and 25 m, respectively, 3) The rooms and the joints are oriented arbitrarily, 4) Forming the room walls that are perpendicular to joints were not preferred, 5) The joint densities in Derinkuyu show ascending tendency, while the joint densities in Kaymaklı have descending tendency from top to ground floors, 6) The joint density of Kızılkaya in the field is higher than the joint density in Derinkuyu underground city. Similarly, the joint density of Gördeles in the field is higher than the density of Kaymaklı underground city, 7) The joint density of Kızılkaya ignimbrite is higher than Gördeles ignimbrite in both field and underground measurements.

Key words: Underground city, Ignimbrite (tuff), joint (fracture), Cappadocia, Turkey

ÖZ

KAPADOKYA BÖLGESİ (TÜRKİYE) DERİNKUYU VE KAYMAKLI YERALTI ŞEHİRLERİNİN JEOLOJİSİ VE ÇATLAK ANALİZİ

Mutlu, Mehmet Özgür

Yüksek Lisans, Jeoloji Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Vedat Toprak

Ortak Tez Yöneticisi: Doç. Dr. Deniz Burcu Erciyas

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Bu tez ignimbrit'lerde oluşan eklemler ile bu birimlerde kazılmış yeraltı şehirleri arasındaki ilişkiyi ve yeraltı şehirlerinin hangi ignibritlerde yer aldıklarını tespit etmeyi amaçlar. Oda pozisyonları, duvar doğrultuları ve eklem doğrultuları çalışmada kullanılan verilerdir. Tanımlanan ilişkiyi inceleme amacıyla Kapadokya'da iki yeraltı şehri (Derinkuyu ve Kaymaklı) seçilmiştir. Birinci şehirde 46, ikincisinde 64 odadan alınan veriler duvar ve eklem yönlerini, eklemlerin oda içindeki konumunu ve eklemelerin yoğunluğunu şehir ve kat bazında incelemek için analiz edilmiştir.

Analizlerden çıkarılan sonuçlar şunlardır: 1) Derinkuyu yeraltı şehri Kızılkaya, Kaymaklı yeraltı şehri ise Gördeles ignimbritinde yer almaktadır, 1) Yeraltı şehirlerinde güneşten istifade amaçlanmadığından duvarlar ve kapıların doğrultuları her yönde dağınıktır, 2) Kızılkaya ve Gördeles ignimbritlerinin arazide ölçülen kalınlıkları sırasıyla 13.5 and 34 metredir. Derinkuyu ve Kaymaklı yeraltı şehirlerinin muhtemel derinlikleri ise sırasıyla 40 ve 25 metredir, 3) Odalar ve çatlaklar düzensiz bir dağılım göstermektedirler, 4) Oluşturulan duvarların eklemlere dik açıyla gelmesinden kaçınılmıştır, 5) Kaymaklı'da eklem yoğunluğu aşağı katlardan yukarı doğru artarken, Derinkuyu'da bu durum tam tersidir, 6) Kızılkaya ignimbritinin arazide ölçülen çatlak yoğunluğu Derinkuyu yeraltı şehrindekinden daha fazladır. Benzer şekilde Gördeles ignimbritinin arazide ölçülen çatlak yoğunluğu Kaymaklı yeraltı şehrindekinden daha fazladır, 7) Kızılkaya ignimbritinin çatlak yoğunluğu hem arazide hem de yeraltında Gördeles ignimbritinin çatlak yoğunluğundan fazladır.

Anahtar Kelimeler: Yeraltı Şehirleri, ignimbrit (tüf), çatlak (eklem), Kapadokya, Türkiye

To my family and Şerife…

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CHAPTER I

INTRODUCTION

1.1. Purpose and Scope

Underground cities are one of the main characteristic features of the Cappadocian region, Central Anatolia, Turkey. Most of the underground settlements are carved within the volcanic rocks in the region between Nevşehir, Niğde, Kayseri and Aksaray. Some of the rooms and houses carved in these rocks are still in use at the present day. The main and common properties of underground settlements related with the building stone are:

- The settlements are totally located beneath the surface except with a small entrance observed at the surface
- The rooms and floors seem to be carved in a disorganized pattern. The irregularity of the settlement is more obvious for the underground cities compared to other type settlements located at the surface. The size and shape of the rooms varies from floor to floor and place to place.
- Most of the settlements observed in Cappadocian region were carved in the ignimbrite (tuff), compatible to be carved, one of the main rocks of the area.
- Ignimbrites have cooling (thermal) joints that are generally developed vertical to the layering of the ignimbrite layers. These cooling joints seen in welded Ignimbrite units consistently have polygonal in plan view. The spacing between the joints varies from meters to ten meters values.

It is obvious that the property of the ignimbrite units to be suitable for carving plays an important role since the ignimbrite is hosting the settlement. The main aim of the study is to investigate geology of the underground cities and the effect of joints present in the ignimbrites on the construction of these settlements.

Rock carved settlements can exist in the area in different patterns. Although there are settlements totally carved at the depth, some other settlements are carved in to cliffs exposed at the surface while some other settlements are partly underground and partly exposed to the surface (Sevindi, 2003). The scope of this study is limited with the underground cities that are totally located beneath the surface.

1.2. Study Area:

Two ancient underground settlements are selected for the measurements in this study. These are typical underground settlements of Cappadocia, Derinkuyu and Kaymaklı. Surely there are some reasons about the selection of these two between the hundreds of underground cities spread in Cappadocia. The criteria applied for the selection of the sites will be mentioned in Chapter 3.1. Location map of the settlements is given in Figure 1.1.

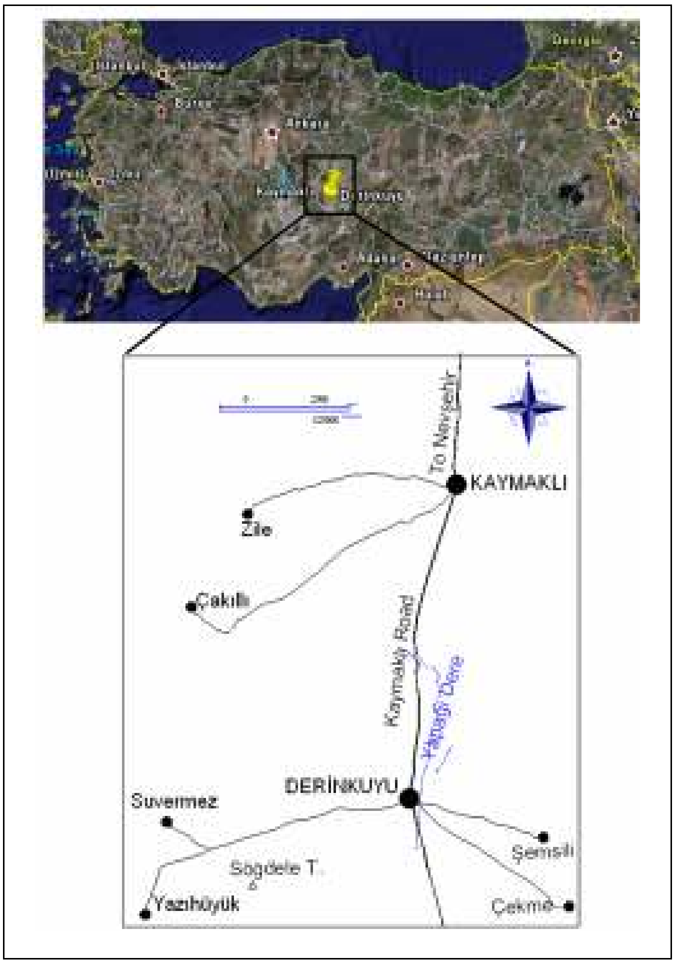

Figure 1.1. Location map showing settlements visited and the detailed maps of selected sites (Derinkuyu and Kaymaklı).

1.3. Previous Works

1.3.1. General Characteristics of Ignimbrites

The term “ignimbrite” has been firstly used Marshall (1935) and the term is introduced into the geological literature. Confusion about the definition of “ignimbrite” still exists, because it is sometimes used as a “litological unit” that means welded tuff, and sometimes as a “genetic” term that means the rock or deposits formed by pyroclastic flows.

According to Sparks et al. (1973) ‘ignimbrite’ is the rock or deposit formed from pumiceous pyroclastic flows irrespective of the degree of welding or volume. Pumice flow deposits, ash-flow deposits and nuee ardente are the terms used for ‘ignimbrite’. Ignimbrites, includes mostly rhyolite, dacite and andesite as composition, are very common volcanic deposits. They can be found in all volcanic settings like oceanic islands, island arcs, microcontinental arcs, continental margin and continental interiors and have been introduced in geological formations in all age.

Dietrich and Skinner (1979) state that welded tuff is the name of pyroclastic rocks, the fragments of which were plastic enough when they were deposited to have been fused. They enounced that “some geologists call all such rocks *ignimbrites*, although that term should be restricted to refer only to welded tuffs of rhyolitic (obsidian) composition.” Welded tuffs have been formed from both ash falls and ash flows. Most such deposits and their consolidated products display stratification as a result of sorting, expressed by graded bedding, of the constituent pyroclasts. Ash flow deposits are made up of pyroclasts travelled rapidly along or near the ground surface after the ejection.

The most important characteristics of ignimbrites are their huge volume erupted during the eruptions, ability of travel large distance from the source vent and coverage of hundreds of km^2. The biggest ignimbrite sheet is the Fish Canyon Tuff in the San Juan volcanic field, have a minimum volume of 3000 km^3. The maximum distance travelled from source is 225 km by Morrinsville ignimbrite.

Sparks et al (1973) indicated that the eruptions indicate a common following sequence of activity:

a) Plinian phase producing a pumice-fall deposits
b) Pyroclastic flow-phase producing ignimbrite and pyroclastic surges and,
c) Effusive-phase producing lava.

It is thought that this sequence stands for the outflow of deeper and less gas-rich levels of magma chamber. Consequently, a plinian eruption will be driven through an ignimbrite-forming one as its column overloads and collapse to produce pyroclastic flows.

Davis (1996) states that joints are fracture surfaces along which there has been imperceptible movement. He indicates that joints occur at the outcrop scale in all rocks and so they are the most widely seen structural element in the Earth crust.

Lobeck (1939) indicates the forces which produce jointing in igneous rocks are:
1) Contraction due to cooling of an igneous mass,
2) Expansion and contraction due to weathering,
3) Pressure as a result of other intrusions,
4) The relief of pressure when overlying material is removed,
5) Larger movements of the earth's crust due to isostatic adjustments
Lobeck states that the joints in igneous rock which are formed due to the contraction on cooling are perpendicular to the cooling surface.

Columnar joints of ignimbrites are the common characteristics of welded ignimbrites (Cas and Wright), although they can be seen in lower degree welded ignimbrites. Thrope and Brown (1993) indicate that texture of pyroclastic flow deposits may become modified during compaction and this is most marked in pumiceous pyroclastic flows named as ignimbrite. The major process welding is the term for post-depositional solidification of hot vesicular fragments (including pumice) and glass pieces during compactions. In the zones of dense welding, the glass pieces and flattened pumice fragments can be detected which forms eutaxitic texture.

Winter (2001) writes that "although models have been proposed for the development of columnar joints, the most widely accepted mechanism is based on contraction of the flow as it cools (Tomkeieff, 1940; Spry, 1962; Long and Wood, 1986; Budkewitsch and Robin, 1994)." As he continues, because the outer areas contracts with the earth and center does not, the top and bottom of the flow cool before the central layers. This inequality results in tensional stress that causes the occurrence of regular joint sets. In order to create polygons separated by joints, blocks pull away from one another by this tensional stress. While cooling progresses (500-800 Cº) toward center to outer layers, the joints grow down from the top and up from the bottom and form the column-like structures. Columns form usually parallel to the surfaces of flow, i.e. horizontal, and perpendicular to the surface. Columns which differ from 5 cm to 3 m in width, generally have 5 or 6 straight and parallel sides, but also may be 4 or 7.

1.3.2. Literature on Cappadocian Ignimbrites

Ignimbrites are one of the main popular rocks types of Cappadocian region that attracted researchers to study several aspects such as geochemistry, geochronology, distribution, mode of occurrence, location of calderas that erupted these ignimbrites etc. Below the studies carried out on these aspects will be explained in chronological order. Stratigraphy and other general characteristics of these ignimbrites will be explained in the next chapter.

Pasquare (1968) is the first researcher who systematically studied and named the Cappadocian ignimbrites. He mapped the area in the vicinity of Ürgüp at 1/25000 scale where most of the ignimbrites are exposed. He attempt to set up the stratigraphy, identified age of the ignimbrites based on paleontological determinations of intercalated sedimentary sequences and draw the boundaries of depositional areas of ignimbrites. He assigned the names for individual ignimbritic eruptions.

Innocenti et al. (1975) investigated stratigraphy, chemical composition and geochronology of ignimbrites in Nevşehir region. The volcanism in the region is defined to be calcalkaline in nature. The main phase of volcanic activity is Middle-

Late Miocene to Pliocene according to the age determinations from different ignimbritic units.

Pasquare et al. (1988) divided the volcanism in Central Anatolia into three main periods, separated by important deformative and erosive events. In the study, first period is represented by a mostly andesitic effusive activity. The second period is characterized by the emplacement of an 11,000 km^2 areal distributed thick ignimbritic sequence. During the third period great andesitic-basaltic stratovolcanoes and a number of prevalently acid monogenic centers developed. They introduce that the probable ignimbrite source vent is Melendiz Dağ volcanic complex and the Çiftlik caldera.

Schumacher et al. (1990) investigated depositional characteristics of ignimbrite. Stratigraphy and depositional characteristics of welded and non-welded ignimbrites are determined and an average age of pyroclastic units is suggested (8.5 m.y.)

Le Pennec et al. (1994) introduced the stratigraphic sequence of Cappadocian Neogene ignimbrites as an old group of ignimbrites (Kavak ignimbrites) followed by five major ignimbrite units (Zelve, Sarımaden Tepe, Cemilköy, Gördeles, Kızılkaya) and two smaller, less extensive ones (Tahar, Sofular). They suggested source areas for these ignimbrites in the Derinkuyu tectonic basin which extends mainly between Nevşehir and the Melendiz Dağ volcanic complex by using five sets of field criteria.

Toprak (1994) defined the Central Kızılırmak Fault Zone (CKFZ) as northern margin margin of The Central Anatolian Volcanic Province (Ürgüp basin) characterized by volcanic rocks and ignimbritic sheets intercalated with lacustrine to fluvial deposits. CKFZ controls the major volcaniclastics. Since there is no volcaniclastic units exist in the north of the CKFZ with the exception of Valibaba unit, youngest ignimbrite, it concludes that CKFZ plays a barrier role for the volcaniclastics and sedimentary rocks.

Topal and Doyuran (1995) studied on both material and mass properties of the tuff to evaluate for the assessment of rock durability. According to this study the Cappadocian tuff is almost fresh, with local discoloration, is moderately weak to very weak, and has low unit weight, very high porosity, and high deformability. The

Cappadocian tuff indicates poor to very poor durability by using various methods for the durability assessment.

Toprak and Kaymakçı (1995) studied slip lineation data developed on the cooling joints of a Pliocene ignimbrite layer measured in the vicinity of Derinkuyu fault to determine the state and the orientation of stresses in the region. They conclude that there is not any direct control of the main fault on the development of the reactivation of preexisting cooling joints, but rather the fault is a result of the present state of stress which reflects a typical example of radial stress field. In this study they determined that the Kızılkaya cooling joints develops in two directions, namely N30-40W and N30-40E. During the reactivation of these joints, one of the directions that is normal to the major fault, N60-80E, is overemphasized. They claim that typical characteristics of columnar cooling joints in Kızılkaya ignimbrite are:

1) Wide spacing,
2) Shape of the blocks (usually tetragonal) bounded by joint planes,
3) Almost vertical surfaces,
4) Slight curvature of the strike and broad undulations of the surface and,
5) Average aperture of 1-2 cm.

Schumacher and Mues-Schumacher (1996) investigated different aspects of Kızılkaya ignimbrite. In the study, the eruptive center was located in the Misli plain northeast of Niğde, as deduced from thickness and grain-size variations of the fall deposit, flow direction indicators, welding patterns of the ignimbrite and the distribution of certain types of xenoliths. They detected two flow units, identified by local pumice enrichment in the upper part of the lower unit.

Topal and Doyuran (1997) investigated Cappadocian ignimbrite according to engineering geological properties and durability assessment. They emphasized both material and mass properties of the tuff to contribute to conservation studies to the historical heritage. These properties were evaluated for the assessment of rock durability. This study shows that the Cappadocian tuff is almost fresh, with local discoloration, is moderately weak to very weak, and has low unit weight, very high porosity, and high deformability.

Schumacher and Mues-Schumacher (1997) studied stratigraphy of Akdağ-Zelve Ignimbrite. In the study the source area is announced about 6 km north-northeast of Kaymaklı. They allocated Ignimbrite as five units totaling up to > 50 m on Akdağ Mountain.

Topal and Doyuran (1998) studied deterioration of the Cappadocian tuff by the aim of understanding the deterioration phenomenon of the tuff to contribute to conservation studies of the historical heritage. In this study, engineering geological and physicochemical characteristics of the tuff were determined.

Temel et al. (1998) set up the stratigraphic column for the Nevşehir plateau based on a number of selected exposed sections on base of petrographic (phenocryst associations, clast morphology, type of xenoliths) and chemical characteristics of ignimbrites investigated the mineralogical, petrographical and geochemical properties (major, trace element and isotope variations) of ignimbrites of Cappadocia. The result of the study shows that assimilation and fractional crystallization processes seem to be the main petrogenetic process in the genesis of Cappadocian ignimbrites. He stated that each ignimbrite exhibits its own mineralogical association and trace-element chemistry that enable stratigraphic correlations (Rb and Sr or Fe, Mg, Mn and Ti contents of biotite) so he contribute the stratigraphy of ignimbrites.

Le Pennec (2000) studied the source location of Kızılkaya ignimbrite by using clast shape preferred orientation or anisotropy of magnetic susceptibility (AMS) data. In this study, geological criteria allowing a rough identification of source vent location are discussed, firstly and, AMS data are processed to more accurately locate the source of this widespread deposit, secondly.

Piper et al. (2002) investigated the magnetic properties of Cappadocian ignimbrite succession. This study deals with the magnetostratigraphy and describes associated rock magnetic properties. As a result, integral magnetic polarity is recognized within each unit and it is determined that most magnetic directions are rotated increasingly clockwise with age.

Schumacher and Mues-Schumacher (2004) investigated areal distribution and bulk rock density variations of the welded İncesu Ignimbrite. In the study, the areal distribution of the ignimbrite indicate that it is strongly controlled by palaeotopography of older volcanic cones and the Taurus mountain belt that channelized individual flow portions and partly terminated their run out.

Le Pennec et al. (2005) examined the chronostratigraphy of mammalian remains recovered in the continental sediments interbedded with the Cappadocia ignimbrites with the aim of reconciling field constraints with paleontologic, radiochronologic, geochemical and paleomagnetic data. The issues faced in this study apply to other ignimbrite provinces in the world.

Steinhauser et al. (2007) investigated the major and trace element concentrations of the Kavak, Cemilköy, Tahar, Gördeles ignimbrites, and the volcanic complexes of Acıgöl and Hasan Dağı by using instrumental neutron activation analysis. Since the distribution of those elements is characteristic of the products of a certain eruption, these elements can be used to establish the origin of an unknown pumice sample by comparison with samples of known origin. In this study, it could be shown that one pumice finding from the excavation in Miletos (Turkey) probably originates from the Hasan Dağı volcanic complex in Cappadocia.

1.3.3. Underground Cities and Rock Settlements in Cappadocia

SİAL (1992), a private geology company, studied the underground cities in Cappadocia in terms of their geological and general properties to be submitted as an improvement report to the Ministry of Culture and Tourism. In this report each underground city is evaluated with respect to the geology and visiting conditions. Summary of this report is illustrated in Table 1.1. Accordingly, both underground settlements are carved in İncesu ignimbrite (which is later modified as Kızılkaya ignimbrite).

Table 1.1: Underground cities in Cappadocia and their physical properties and geological units (SİAL, 1992) (Original table translated to English).

No	Name of Underground Cities	Rock Formation	Member	Visiting	Cleanliness, lightening and transportation
1	KAYMAKLI	Ürgüp	İncesu	Open	Good
2	DERİNKUYU	Ürgüp	İncesu	Open	Good
3	ÖZKONAK	Ürgüp	Kavak	Open	Good
4	MAZI	Ürgüp	Tahar and İncesu	Open	Inadequate
5	ACIGÖL	Karnıyarık Tepe Basalt		Open	Good
6	TATLARİN	Ürgüp	Kavak	Open	Good
7	GÖKÇETOPRAK	Ürgüp	İncesu	Closed	Absent
8	KURUGÖL	Basaltic Cinder Cone		Closed	Absent
9	OVAÖREN	Ürgüp	İncesu	Closed	Absent
10	İĞDELİ	Ürgüp	İncesu	Closed	Absent
11	AĞILLI	Ağıllı		Closed	Absent
12	DOĞALA	Melendiz Mountain Andesite		Closed	Absent
13	SUVERMEZ	Karnıyarık Tepe Basalt		Closed	Absent
14	ÇAKILLI	Ürgüp	İncesu	Closed	Absent
15	ÖZLÜCE	Kumtepe Ash and Melendiz Andesite		Open	Inadequate
16	TİL	Ürgüp	İncesu	Closed	Absent
17	AYVALI	Ürgüp	Kavak	Closed	Absent
18	AKSALUR	Ürgüp	Bayramhacılı	Closed	Absent
19	SOFULAR				
20	MAHMATTATAR	Ürgüp	Kavak	Closed	Inadequate
21	GÖYNÜK	Ürgüp	Asarcık Dere	Closed	Absent
22	YALLIDAMI	Ürgüp	Asarcık Dere	Closed	Absent
23	AYAZMA	Ürgüp	Kavak	Closed	Absent
24	YEŞİLÖZ	Ayhan	Saytepe	Closed	Absent
25	GÜMÜŞKENT	Ürgüp	Asarcık Dere	Partly Open	Absent
26	SIĞIRLI	Peçenek		Partly Open	Absent

Gülyaz and Yenipınar (1996) attempt evaluate distribution and locations of main underground cities in Cappadocia. According to them there are 22 known large-scale underground cities in the Cappadocia Region (Figure 1.2). Hundreds of rooms in the underground cities were connected to each other with long passages and labyrinth-like tunnels. The corridors are long, low and narrow to restrict the movement of intruders. There are stone doors between the floors that can be opened only from the inside and are 1–1.5 m in diameter and 30–35 cm thick.

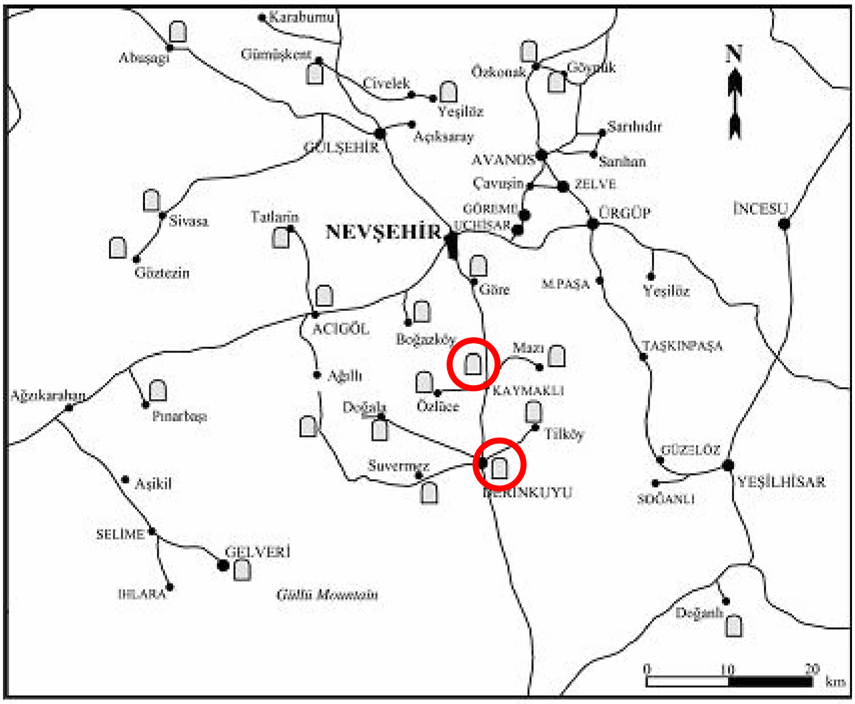

Figure 1.2. Location of main underground cities in the Cappadocia Region (after Gülyaz and Yenipınar, 1996). Red circles indicate underground cities investigated in this study.

Aydan et al. (1997) investigated local and global rock failures in the underground cities. Several approaches were applied about how to assess the strength of rock masses together with some new proposals for underground excavations.

Ünver and Ağan (2003) investigated underground food storage openings in the Cappadocia Region and their potential use for frozen food storage. Heat transfer around openings for various geometrics in three-dimensions has been modeled by using a finite element software.

Sevindi (2003) studied the relationship between the joints developed in the ignimbrites and the cliff settlements carved in the same units. Two sites in Cappadocia, Eskigümüşler and Çanlıkilise, were investigated and two questions were asked. These are 1) whether the joint density plays a role on the selection of sites and, 2) are the joints taken into consideration when the settlements were carved.

Aydan and Ulusay (2003) studied physical and short-term mechanical characteristics and the in situ characterization of the Cappadocia tuffs. In the study, possible engineering geological problems at Cappadocia with mechanical aspects of historical and modern rock structures and their implications in rock engineering is concerned.

Ayhan (2004) investigated the effect of rock types and morphologic classes on the locations of underground cities existing in Cappadocia. In this study the main point is whether the dwellers of the underground cities had considered one or more controlling factor(s) to carve an underground city, particularly rock type or morphology.

Ulusay et al. (2006) investigated the environmental and engineering geological problems for the possible re-use of abandoned rock-hewn settlements in Ürgüp. In this study, rock fall potential and stability of about 1200 rock-hewn structures were investigated and an inventory was prepared for the possible re-use of the underground openings.

1.3.4. Historical Aspects of the Underground Cities

One of the earlier questions that the researchers try to answer about the underground cities is why the ancient people built these cities. The other major questions are who did it, when the settlement was dig and how they built it, etc. Unfortunately there is no written source that we can learn the answers from the ancient men. Nevertheless, researchers extract some results in light of regional, historical, environmental, archaeological and geological factors.

Erguvanlı and Yüzer (1977) categorized the factors for the underground settling in Cappadocia and the use of ignimbrite as follows:

1. Severe daily and seasonal changes of temperature in the region,
2. Thermal isolation properties of the rock units covering the region,
3. Self-supporting behavior and construction opportunities of rocks,
4. Easily carved, particularly soft tuffs,

5. Defensive advantage and safety against enemy attacks for hiding and camouflage,
6. Superior resistance and protection against natural disasters such as earthquake and/or volcanic eruptions.

Korat (2003) emphasized that the underground cities are the oldest architectural components of Cappadocia. It is obvious that these underground cities had been used as simple cave shelters in the Neolitic Era; were transformed by Hittite and Phrygia civilizations in time and were developed by the Romans as it takes its latest form at the time of the Byzantines.

Derinkuyu is an ancient settlement that has 55 meters depth with eight floors and spreads over 500 square of meters area; however, its real areal distribution is not exactly known today. There are kitchens, cellars, wine storages, stables in the first two floors; living rooms, churches and tunnels in the third and fourth floors. These tunnels are thought to have a connection with the other underground cities around Derinkuyu and the tunnel in the third floor is thought to have a connection with Kaymaklı underground city which is 9 kilometers away. This tunnel has approximately 2 meters width and 2 meters height.

Derinkuyu, which was named as ‘Melogobia’ (Gülyaz and Yenipınar; 2003), is the most important center that reflects the civil life in Cappadocia. It is a model settlement not only in showing the underground settlement but also in combining the components such as defense, air conditioning and water systems.

However, Erguvanlı and Yüzer (1977) stated that the Derinkuyu Underground City (Figure 1.3) has 2500 m2 covering area and a total depth of 85 m from the ground surface. There are a total of 52 ventilation chimneys and their length varies between 70 and 85 m. It is seen that the difference between covering area measurements and the detected depth in the previous studies stem from the lacking of information of its real areal extents and the accepted reference level to measure the depth. In some researches, researches accept the reference level as the bottom of ventilation shafts, some of them as the bottom of water shafts and some of them as the bottom of settlement.

Gülyaz (1998) indicates that the depth of Derinkuyu is 40 meters according to ventilation shaft just near the entrance and 85 meters according to the water shaft that has no connection to the surface.

Gülyaz and Yenipınar (2003) states that although some researchers claim that the underground settlements were connected to each other with tunnels, no conclusive evidence to support this idea has been found so far.

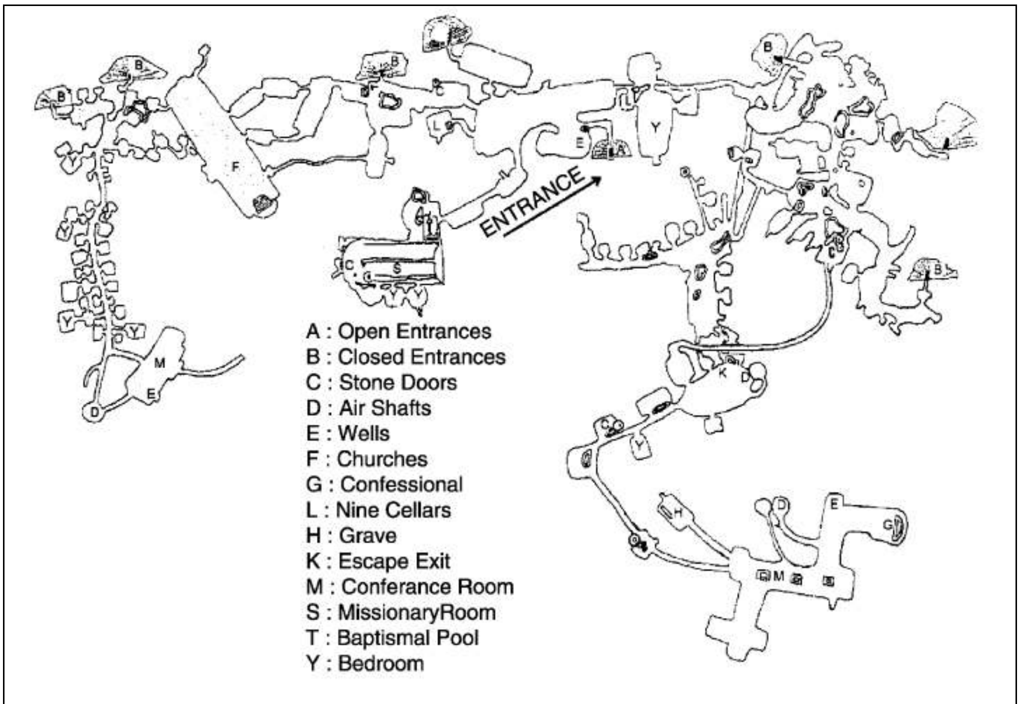

Figure 1.3. Plan of the Derinkuyu underground city (after Gülyaz and Yenipınar, 1996).

Kaymaklı underground city, which was named as 'Melogobia' (Gülyaz and Yenipınar, 2003) is said to have accommodated 60,000 people. Today, small halls and rooms with tunnel-like passages between them, large kitchens, large polished pits used as water cistern and wine cellars, storage rooms, little chapels and ventilation chimneys can be seen. Only four floors are open to the visit (Aydan and Ulusay, 2003).

In the book Cappadoica (1988) it is said that it simple lines and continuous reutilization have made it impossible to technically judge the date of foundation; some pages of Xenphon's Anabasis seem to refer to the village of Kaymaklı. If the underground city with entrances similar to the wells, in which men descended with ladders and animals through tunnels, was in fact Kaymaklı, one could quite rightly say that the town has been inhabited since the V century B.C.

Cimok (1987) states that there is no evidence to tell us whether the whole or some parts of the Kaymaklı settlement were occupied at one or another particular time. In his “Anabasis”, Xenophon gives us a description of a similar underground village.

Gülyaz and Yenipınar (2003) state that the earliest document source about the underground cities is Xenephon’s book, ‘Anabasis’. In this book it is mentioned that the people lived in Anatolia and Caucasia hollowed their houses under the ground and these houses were connected to each other with tunnels. It is possible to date the underground cities exactly the 4th century B.C, the date of the Xenephon lived. They also stated that the first serious research in the region was performed by Martin Urban between 1960 and 1970. Urban dated the underground settlements to the 7th and 8th centuries B.C.

1.4. Method of Study

The main steps of the method that guided us through the study are listed below.

In the first step the literature available about the Cappadocia Volcanic Province and underground settlements is complied. Between the candidate settlements two sites were selected for the study.

The second step is collecting the data from settlements and in the field. Underground cities and field visited several times and room and field measurements were applied. In the collection of data Brunton compass and 5m long steel tape were used.

The third step includes the performing of analysis. Database, sketch diagrams, rose diagrams. Histograms are prepared by using Netcad 5.0 GIS, Rockworks 2007 and Excell 2002 softwares.

1.5. Organization of Thesis

This thesis includes seven chapters. A brief description of each chapter is given below.

Chapter 1 deals with the definition of the problem and gives information about the study area followed by the literature about the general aspects of ignimbrites and underground cities.

Chapter 2 is the literature survey about the geology of study area. Stratigraphy of the area and fault systems is explained in this chapter, briefly.

Chapter 3 explains the geology of Derinkuyu and Kaymaklı underground cities. Morphology of the area, stratigraphy of the area, geology of underground cities including ignimbrite units within which the settlements carved; characteristics of the ignimbrites and the boundaries detected between the units in the field, geologic maps of the cities, and the depth of the settlements are the main parts of this chapter.

Chapter 4 is about the data collected in this study. The chapter starts with the criteria used for selection of sites, a flowchart of the study steps followed by the details of the data collected from field and underground cities including the sketch drawings of rooms measured. These data include room, wall and joint measurements.

Chapter 5 includes the analysis of the data presented in previous chapter. The analyses are grouped into two as field analysis and underground city analysis. These analyses are directional, density analysis and visual interpretations.

Chapter 6 is the discussion chapter includes the lack of data; methods applied in the study and interpretations of results parts.

Chapter 7 is the last chapter about the conclusions and the recommendation for the further studies.

CHAPTER II

REGIONAL GEOLOGY

2.1. Geological Setting

The study area is located in the Cappadocian Volcanic Province (CVP that extends in NE–SW direction for a length of 300 km and a width of 20–50 km (Figure 2.1.) The CVP is one of Neogene-Quaternary volcanic fields of Turkey located in central Anatolia. The volcanic activity of the CVP is investigated by several researchers dealing with various aspects such as chronology, petrographical and geochemical characteristics, and ignimbrite emplacement (Pasquare, 1968; Innocenti et al., 1975; Besang et al., 1977; Pasquare et al., 1988; Ercan et al., 1990, 1992; et al., 1994; Le Pennec et al., 1994, Temel et al., 1998; Schumacher and Mues-Schumacher, 1996). According to these studies the CVP is a calc-alkaline volcanic province formed by the convergence between Eurasian and Afro-Arabian plates occurring in the eastern Mediterranean.

2.2. Stratigraphy

Volcanic rock units determined in CVP are grouped into four categories from bottom to top by Toprak (1998): 1) Mio-Pliocene volcaniclastics, 2) Miocene-Quaternary volcanic complex, 3) Quaternary basalts and cinder cones, 4) Plio-Quaternary continental clastics (Figure 2.1). Since the ignimbrites (Mio-Pliocene volcaniclastics) are the main concern of this study, these rocks will be explained in detail and brief descriptions of others are given below.

2.2.1. Mio-Pliocene Volcaniclastics

Mio-Pliocene volcaniclastic deposits are named as Ürgüp formation by Pasquare (1968). The formation is composed of volcaniclastic deposits (mainly ignimbrite) intercalated with lacustrine to fluvial sedimentary rocks. The total thickness of the formation is more than 400 m. About 10 ignimbritic layers are recognized within

Ürgüp formation (Pasquare´, 1968; Innocenti et al., 1975; Pasquare´ et al., 1988; Schumacher et al., 1990; Le Pennec et al., 1994; 2005). Generalized columnar section of the formation is given in Figure 2.2. It should be noted that there is inconsistency in the names given to the ignimbrites in the formation. This inconsistency sometimes can extend to the stratigraphic position of the ignimbrites. To avoid this problem the nomenclature in the most recent publication (Le Pennec, et al., 2005) will be adopted here. Pasquare (1968) defines Ürgüp Formation as "a rock-stratigraphic unit of continental facies represented essentially by pelitic lithotypes of various grain-size with diffused pyroclastic contaminations and recurrent ignimbritic episodes." They divided the Ürgüp formation into 18 units.

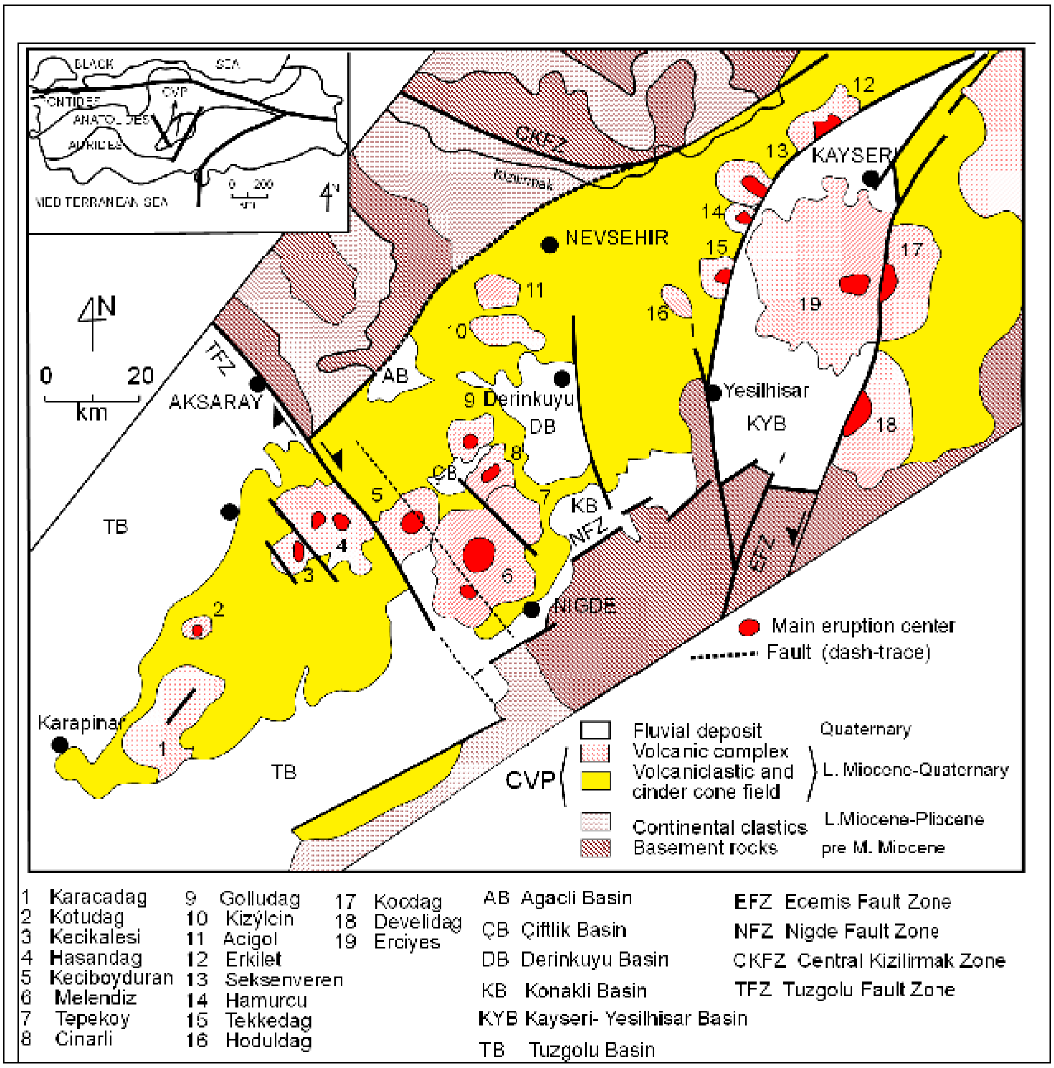

Figure 2.1. Simplified geological map of the Cappadocian volcanic province (CVP) (Toprak, 1998).

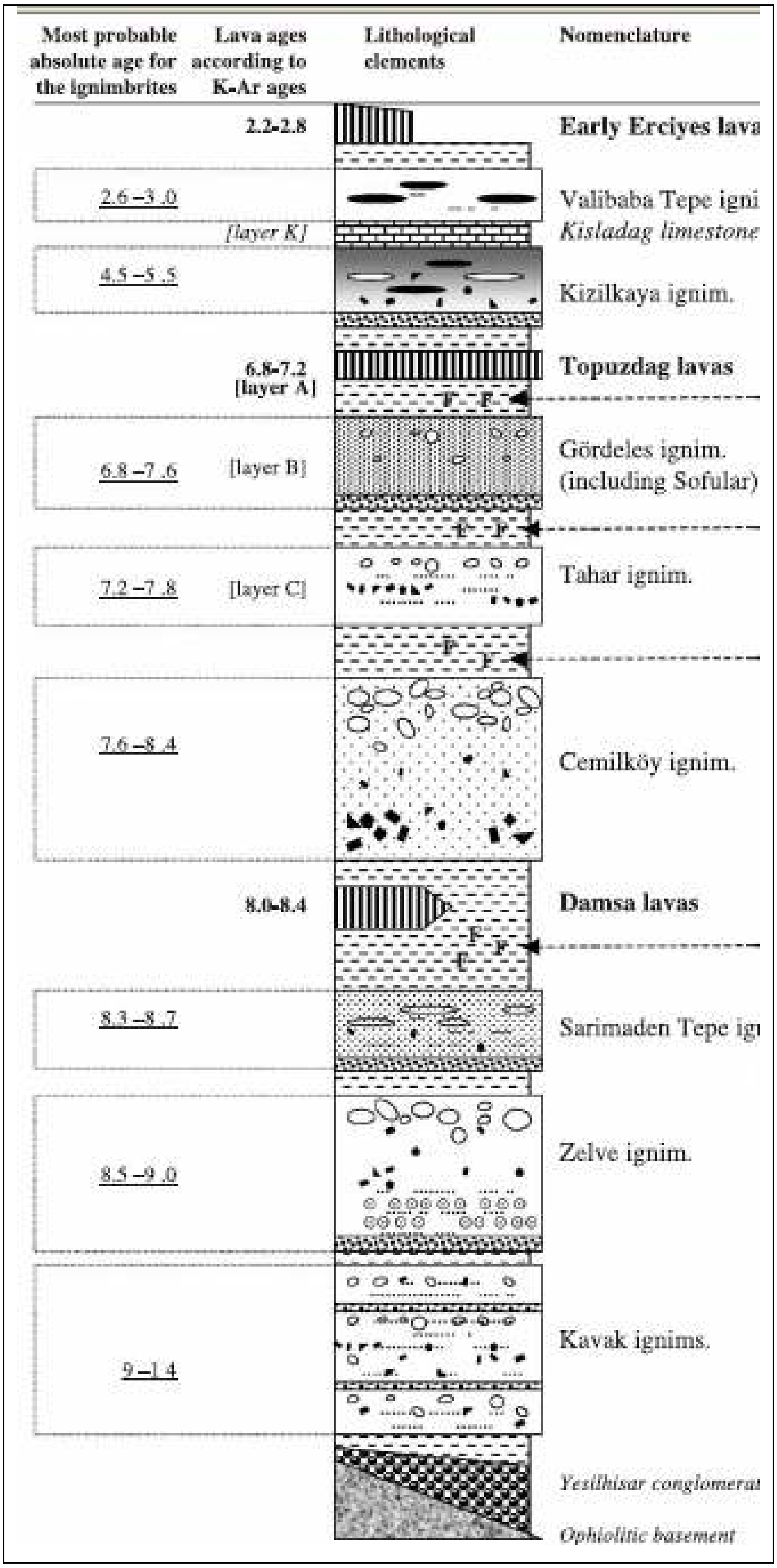

Figure 2.2. Stratigraphic columnar section of Cappadocian ignimbrite succession "Ürgüp formation" (Le Pennec et al., 2005).

Sedimentary units within the Mio-Pliocene volcaniclastic deposits are characterized by volcanic conglomerates and pelitic rocks at the base, by marls and fine-grained slightly tuffaceous sandstones in the middle part and by clay minerals, marls and lacustrine limestones at the top (Pasquare, 1968). These sedimentary units are named as Hacıbayramlı member (Pasquare, 1968) and Çökek member (Temel, 1992).

The palaeontological data, recognized at different stratigraphic positions in the sequence, show that the age of the units are between Maeotian (Late Miocene) and Pontian (Late Miocene-Pliocene) (Şenyürek, 1953; Pasquare, 1968). This age is conformable with the radiometric ages of the associated ignimbritic units identified by Innocenti et al. (1975). Le Pennec et al (2005) studied about the chronostratigraphy of mammalian remains recovered in the continental sediments interbedded with the Cappadocia ignimbrites. In this study a detailed comparison is performed between the previous studies performed about the age and the stratigraphic correlations and interpretations (Figure 2.2). Accordingly, the ignimbrites are erupted in the range of 14 to 2.6 Ma.

According to columnar section there are eight major ignimbritic eruptions in the region. These ignimbrites (bottom to top: Kavak, Zelve, Sarımaden Tepe, Cemilköy, Tahar, Gördeles, Kızılkaya and Valibaba Tepe) are briefly explained below.

Kavak Ignimbrite: The Kavak member is identified to be the first ignimbritic activity took place in the area. Its thickness varies from 30 to 40 meters along the western side of Sultansazlığı Depression (Pasquare, 1968). Near Göreme, it reaches to a thickness of 95 m. The ignimbrite includes ash-fall and flow deposits interbedded with volcanic-clastic sediments. It covers an area of 2600 km^2, having a volume of 80 km^3. Kr-Ar dating gives ages of 8.6–11.2 Ma (Innocenti et al., 1975; Temel, 1992; Le Pennec et al., 1994) and 9.0-14 Ma (Le Pennec et al., 2005). The source of this ignimbrite is situated in an area between Nevşehir and Derinkuyu.

Zelve Ignimbrite: The Zelve ignimbrite, which has 4200 km^2 areal distribution and 120 km^3 volume, is composed of a single pyroclastic flow unit. According to Pasquare (1968) this unit is a part of Tahar ignimbrite. Average thickness of the ignimbrite is 60 m which reaches to 100 m thickness. At the Özkonak Underground

City the unit has a thickness between 10 m to 15 m according to Le Pennec et al. (1994). The source area is the same with the Kavak member (Le Pennec et al., 1994). In the north, Temel and Gündoğdu (1998) indicate that the ignimbrite is altered extremely. Age of the unit is 8.5 to 9.0 according to Le Pennec et al (2005).

Sarımaden Tepe Ignimbrite: The Sarımaden Tepe ignimbrite is a massive thick-bedded ignimbrite, which is found also in the zone of gently undulated reliefs excavated in the Neogene series SE of Nevşehir (Pasquare, 1968). The thickness of the unit is 4 to 5 m. This ignimbrite is well seen in Sarimaden Tepe and is composed of a welded pyroclastic flow unit with well developed columnar jointing. It has 80 km^3 volume and 3900 km^2 outcrop area. The K–Ar age of this ignimbrite is 8–8.6 Ma according to Innocenti et al. (1975) and 7.6-8.4 Ma according to Le Pennec et al. (2005). The source area is located around Derinkuyu (Le Pennec et al., 1994).

Cemilköy Ignimbrite: The Cemilköy Ignimbrite represents a very characteristic morphological feature characterized by conical fairy chimneys between Ürgüp and Nevşehir, and in the valley of Damsa Çay. The thickness varies between 40 m to 110 m (Pasquare, 1968). Le Pennec et al. (1994) indicate its volume as 300 $km^3$and its extent area as 8600 km^2 and proposed south of Derinkuyu as a source. Temel et al. (1998) indicate that; "Its lithic fragments differ from those of other ignimbrites, being represented by gabbro and pyroxenite-type rocks derived from the ophiolitic basement". It is age is between 7.6 and 8.4 (Le Pennec et al., 2005).

Tahar Ignimbrite: Tahar unit described at Tahar village by Pasquare (1968) initially as a lahar deposit. Later the unit is interpreted as an ignimbrite by Pasquare et al. (1988). He suggested an average thickness of 40 m with the recorded maximum thicknesses as 63 m near Karain and 80 m near Tahar Village. Its areal distribution is about 1000 km^2 and its volume is about 25 km^3. Tahar Ignimbrite is composed of several pyroclastic flows, some of which are rich in lithics containing mostly basalt and andesite-type lava fragments (Temel et al., 1998). Its source area is located near Hodul Dağ (Le Pennec et al., 1994). This ignimbrite is rather compact but not welded and, in the Sofular region, it shows regular columnar jointing. It has a 7.2-7.8 Ma age according to Le Pennec et al. (2005).

Gördeles Ignimbrite: The Gördeles Ignimbrite was first defined by Pasquare (1968). According to Le Pennec et al. (1994) the unit, located to the west, east and southeast of Nevşehir Plateau, covers 3600 km^2 area and has a volume of about 110 km^3. Its average thickness is 10-20 m, and maximum thickness was measured as 50-100 m on the Şahin Kalesi massif. On this location, the unit contains high content of lithic clasts and lag breccia facies. The location of source is identified close to the northern edge of the Şahin Kalesi massif by using flow indicators showing southward direction. It is composed of a single pyroclastic flow deposits. The lower part of the unit contains a fine-grained matrix and large amounts of biotites. K-Ar age is about 7.8 Ma according to Innocenti et al. (1975). Le Pennec et al., (2005) indicate the age as 6.8-7.6 Ma.

Kızılkaya Ignimbrite: 'Kızılkaya ignimbrite' (Batum, 1978) corresponds to the 'Incesu Member' member of Pasquare (1968). Le Pennec et al. (1994) identified that the Kızılkaya ignimbrite, the most extensive unit in Cappadocia, covers an area between Nevşehir, Kayseri and Niğde as a horizontal sheet (Pasquare, 1968; Pasquare et al., 1988). Its thickness varies between 4 to 60 meters, and it overlies an ash-fall layer with a maximum thickness of 20 cm. According to Innocenti et al. (1975) and Besang et al. (1977), the age is 4.4 to 5.5 Ma. Mues Schumacher and Schumacher (1996) shows the age as 4.3-5.5 Ma and Le Pennec et al. (2005) shows the most probable age as 4.5-5.5 Ma. The source is located in the southwestern part of the Derinkuyu plain (Le Pennec et al., 1994).

Valibaba Tepe ignimbrite: The Valibaba Tepe ignimbrite, identified by Pasquare (1968), is the youngest ignimbrite and has a great areal extension with average thickness of 5-15 m. Its outcrops can be seen mainly on the eastern part of Nevşehir Plateau. Le Pennec et al. (1994) estimate its areal extension and volume as 5200 km^2 and 100 km^3, respectively. Valibaba Ignimbrite has been dated as 2.7-3.0 Ma by Innocneti et al. (1975) and 2.2-2.8 Ma by Le Pennec et al. (2005). Its source location is Kayseri area according to Pasquare et al. (1988). There are two flow units with columnar jointing. It has oxide grains that richer in Ti in comparison to oxides in other ignimbrites (Temel et al., 1998).

Two ignimbrites of interest for this study are Kızılkaya and Gördeles since the underground cities of this study are located in these ignimbrites. The sources of these ignimbrites as suggested by Le Pennec et al (2005) are illustrated in Figure 2.3. The importance of the source is that, the study area is close to these sources and the thicknesses of the units are supposed to be thick in the vicinity of the source area.

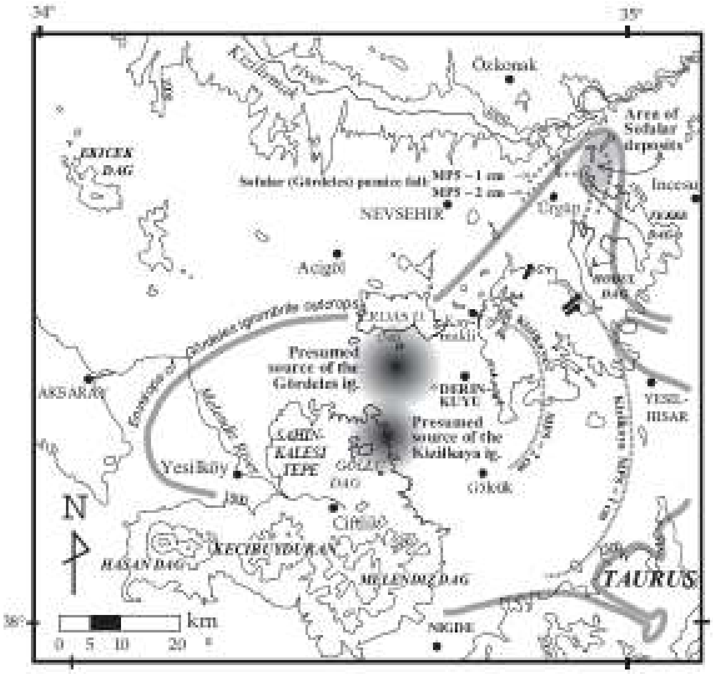

Figure 2.3. Presumed sources of Kızılkaya and Gördeles ignimbrites (Le Pennec et al., 2005).

2.2.2. Miocene-Quaternary Volcanic Complex

Miocene-Quaternary volcanic complex consist of major eruption centers in the CVP. There are nineteen eruption centers are identified within the CVP. Most of the centers are characterized by huge topographic masses erected above a base level of 1050 m altitude. The volcanic complex shows a parallelism with the NE–SW elongation of the CVP that is the direction of the Mio-Pliocene CVP fault system (Toprak, 1998). These are polygenetic volcanoes that are composed of the products of many eruptions with a central eruption vent of a few kilometers in diameter (Göncüoğlu and Toprak, 1992). The highest volcano is Erciyes volcano with its 3917 m elevation.

2.2.3. Quaternary Basalts and Cinder Cones

Quaternary Basalts and cinder cone units consist of monogenetic (parasitic) eruptions that are single eruptions and mostly associated with vents aligned on dike-like tabular conduits and their lava flows. There are more than 800 monogenetic volcanoes within the CVP. Most of these volcanoes are in the form of cinder cones although some exist as rhyolitic or andesitic domes and maars. (Pasquare, 1968; Keller, 1967; Batum, 1978a). The diameters and heights of the cinder cones ranges between a few tens of meters to 1-1.5 kilometers, and a few tens of meters to a few hundred meters, respectively. They are all associated with basaltic lava and their ages are late Quaternary (Ercan et al., 1990; 1992; 1994; Bigazzi et al., 1993). While Rhyolitic domes, Quaternary in age, are identified around the Acıgöl caldera, commonly (no. 11, Figure 2.1), Andesitic domes, from late Miocene to Quaternary in age, are mostly identified in the area between Nevşehir, Derinkuyu, and Yeşilhisar.

2.2.4. Plio-Quaternary Continental Deposits:

Plio-Quaternary continental deposits which cover large areas are displayed within isolated 7 basins developed under the influence of tectonic and volcanic structures existing within the CVP (Toprak, 1996). Most of the basins are filled with fluvial clastics and all of them evolved in the main depression of the CVP. These depressions are equal in age to the age of the youngest unit of Ürgüp Formation. So, their age is Plio-Quaternary with minor variations from place to place.

2.3. Fault Systems

Underground cities analyzed in this study are located in the close vicinity of the faults. Therefore, brief information will be given on the faults existing in the area. According to Toprak and Göncüoğlu (1993), two fault systems in different age and nature were determined within the Cappadocian Volcanic Province (CVP). These are 1) The Tuzgölü-Ecemiş fault system and, 2) The CVP fault system.

The Tuzgölü-Ecemiş system is a fault swarm located between the conjugate Tuzgölü fault in the west and the Ecemiş fault in the east (Figure 2.1). The Tuzgölü fault has a length of more than 150 km and a vertical offset of more than 300 meters and defines the eastern margin of the Tuzgölü basin (Uygun, 1981). The Ecemiş fault with a total length of about 600 km (Beyhan, 1994) cuts across the CVP in its eastern part. Other major faults within this system are the Keçiboyduran–Melendiz (Toprak and Göncüoğlu 1993) and Derinkuyu (Toprak and Kaymakı, 1995) faults. Activity intervals of these faults is illustrated in Figure 2.4 for three periods, namely, a) pre-mid Miocene, b) Mid-Miocene to early Pliocene, and c) late Pliocene to Quaternary.

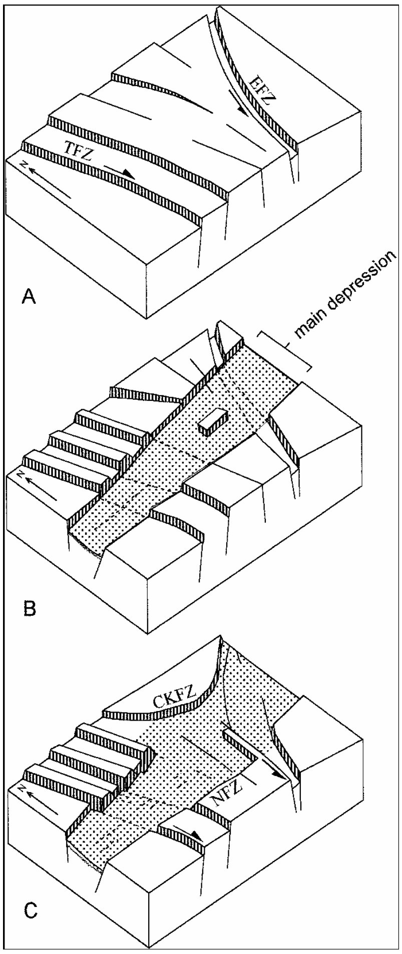

Figure 2.4. Sketch block diagrams illustrating the behavior of two faults systems for the Mio-Quaternary period and the formation of the CVP main depression (Toprak and Göncüoğlu, 1993). A) Pre-Mid Miocene, B) Mid-Miocene to Eearly Pliocene, C) late Pliocene to Quaternary. (CKFZ: Central Kızılırmak faultzone; DF: Derinkuyu fault; EFZ: Ecemiş fault zone; GF: Göllüdağ fault; KMF: Keçiboyduran-Melendiz fault; NFZ: Niğde fault zone; TFZ: Tuzgölü fault zone).

Derinkuyu Fault is one of the major faults in the area and is closely located to the two underground settlements of this study. The fault defines the eastern margin of the Derinkuyu Basin. It is oriented approximately N-S, makes a curvature at its northern tip, and strikes to NNW-SSE. It has a continuous scarp of about 20 km with the eastern block being uplifted. The amount of the vertical throw is estimated to be 50 m (Toprak and Kaymakçı, 1994).

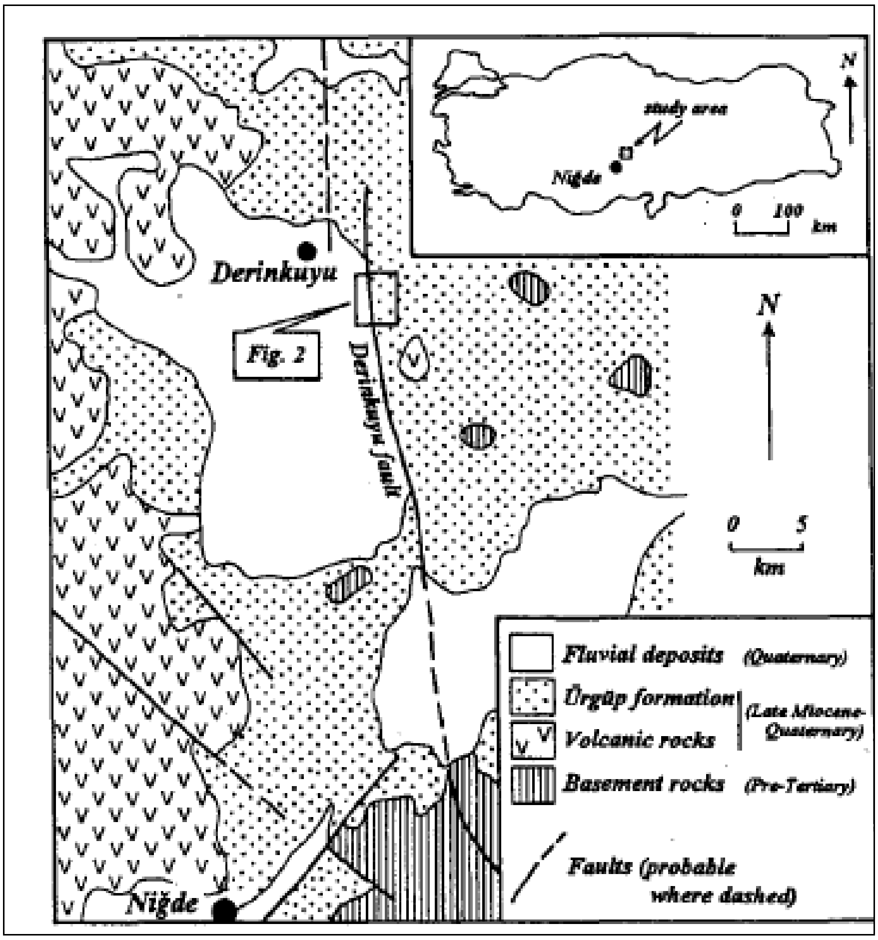

Figure 2.5. Geologic map showing the regional setting of the area and Derinkuyu Fault (Toprak and Kaymakçı, 1994).

CVP faults strike NE–SW, parallel to the long axis of the CVP. Two major faults of this system are the Central Kızılırmak (Toprak, 1994) and Niğde faults which define the northern and southern margin of the volcanic depression, respectively (Figure 2.1).

CHAPTER III

GEOLOGY OF UNDERGROUND CITIES

This chapter deals with the geology of the area (both the close vicinity of the sites and the rock units within the underground cities). The chapter is divided into four sections. In the first two sections morphology and stratigraphy of the area will be introduced. This will be followed by two sections where details of geology will be given first for Derinkuyu and then for Kaymaklı underground cities.

3.1. Morphology of the Area

Morphology of the area where Derinkuyu and Kaymaklı underground cities are located is shown in Figure 3.1 prepared from 1/25.000 scale digital topographic maps. The area is mostly situated at the topographic interval of 1300 to 1500 m. Circular features in the figure correspond to volcanic eruption centers. Blue area is the flat surface that represents north-eastern part of the Derinkuyu Basin. The area east of Derinkuyu fault (orange color) is composed of ignimbrites namely Kızılkaya and Gördeles.

Derinkuyu and Kaymaklı underground cities are located on almost flat surfaces with average elevations of 1355 and 1420 m, respectively. Both sites are located on the downthrown blocks of the faults located to their east. Derinkuyu fault is the major structural element in the area (Figure 3.2). Abrupt termination of drainage (small NE-SW streams) along the fault is an important indication of the fault. This termination indicates the eastern margin of the Derinkuyu basin.

Kaymaklı underground city, on the other hand, is located to the west of a NE-SW striking fault. The relationship between this fault and Derinkuyu fault is not clear.

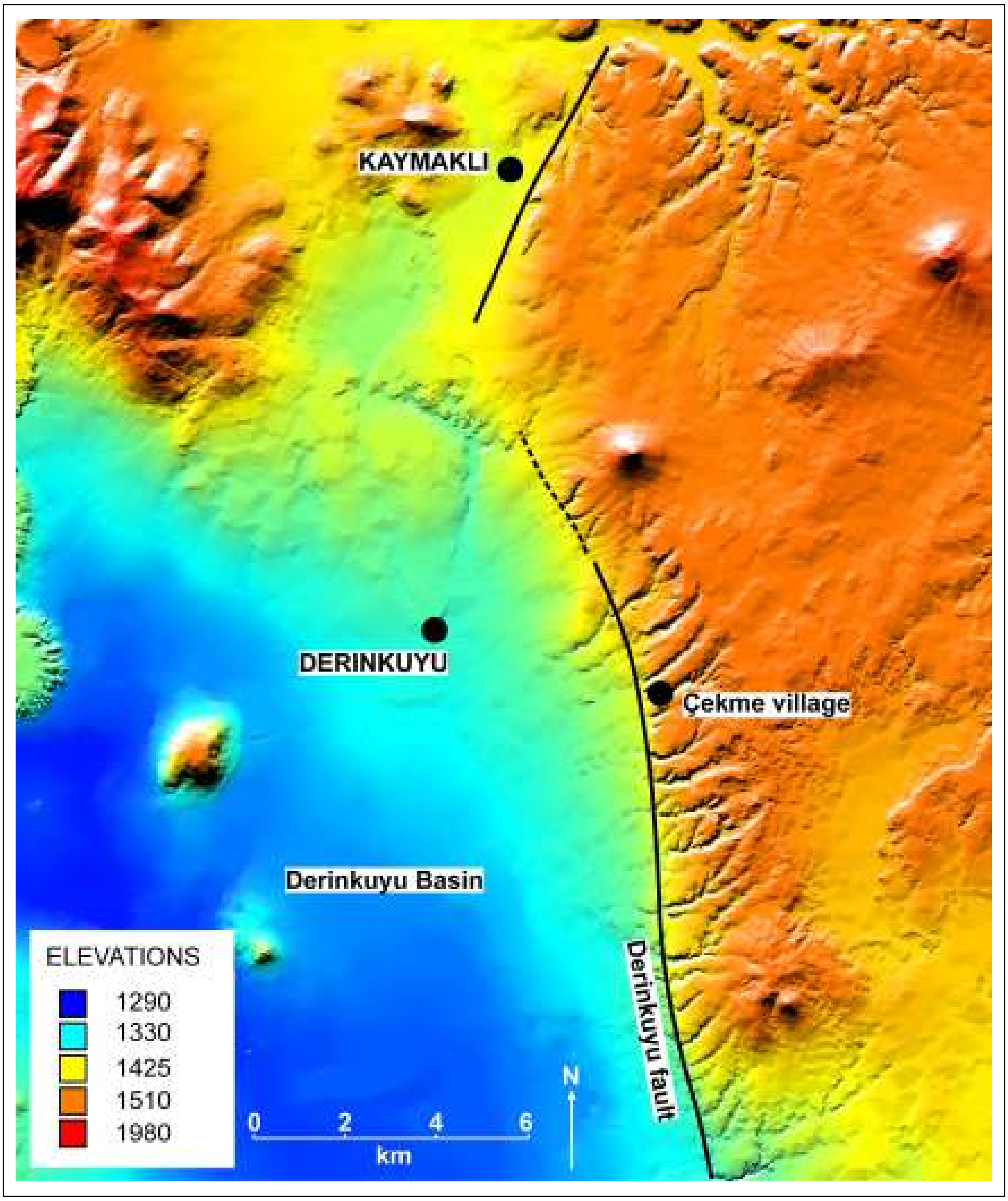

Figure 3.1. Relief shaded digital elevation model of the area.

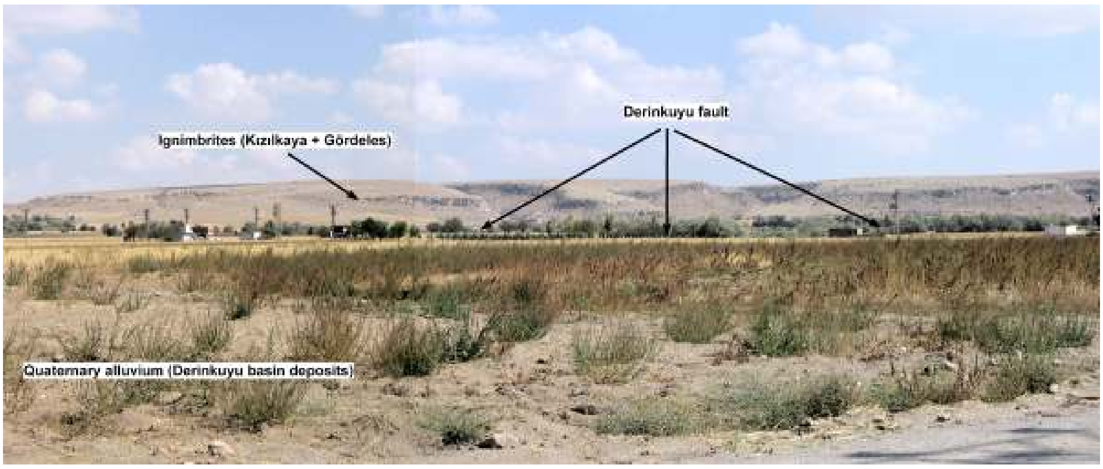

Figure 3.2. General view of Derinkuyu fault (looking eastward, east of Derinkuyu)

3.2. Stratigraphy of the Area

Derinkuyu and Kaymaklı underground cities are carved within the Kızılkaya and Gördeles ignimbrites, respectively. These two ignimbrites are located in the uppermost section of Ürgüp formation (illustrated in Figure 2.2). A stratigraphic section measured near Çekme village is illustrated in Figure 3.3. A general view of this section is shown in Figure 3.4.

The basal part of the section is represented by 34 m thick Gördeles ignimbrites. The unit is characterized by grey, massive ignimbrite with large irregular pumice fragments. Columnar joints are commonly observed with narrow (1-2 mm) apertures.

Kızılkaya ignimbrite is found at the top of the sequence. The unit has an observable thickness of 13.5 m with flattened pumice fragments. The unit is welded and therefore resistant to the erosion. For this reason it forms mesa-like landforms in the region. Vertical columnar joints are well developed in the unit with an average aperture of 1-2 cm.

There is a layer of fluvial clastics between Kızılkaya and Gördeles ignimbrites (Figure 3.5). The unit is represented by semi-consolidated to consolidated brown claystone and siltstone. The thickness of the unit in the measured section is about 2.5 m. This unit, however, is not a local deposit but rather a distinguishing layer that exist between these two ignimbrites at regional scale. Reconnaissance trips made to different parts of the area indicate that:

- Fluvial clastics are the key horizon and exist at long distances from the sites; therefore, can be used as a tool in the underground cities to distinguish the boundary of Kızılkaya and Gördeles ignimbrites. Figure 3.6 shows an example of this unit around Mazıköy village which is famous with its underground city.
- The thickness of this unit increases eastward and reaches more than 20 meters as observed in deeply dissected valleys between Derinkuyu and Yeşilhisar cities. An example of thick fluvial clastics is shown in Figure 3.7.

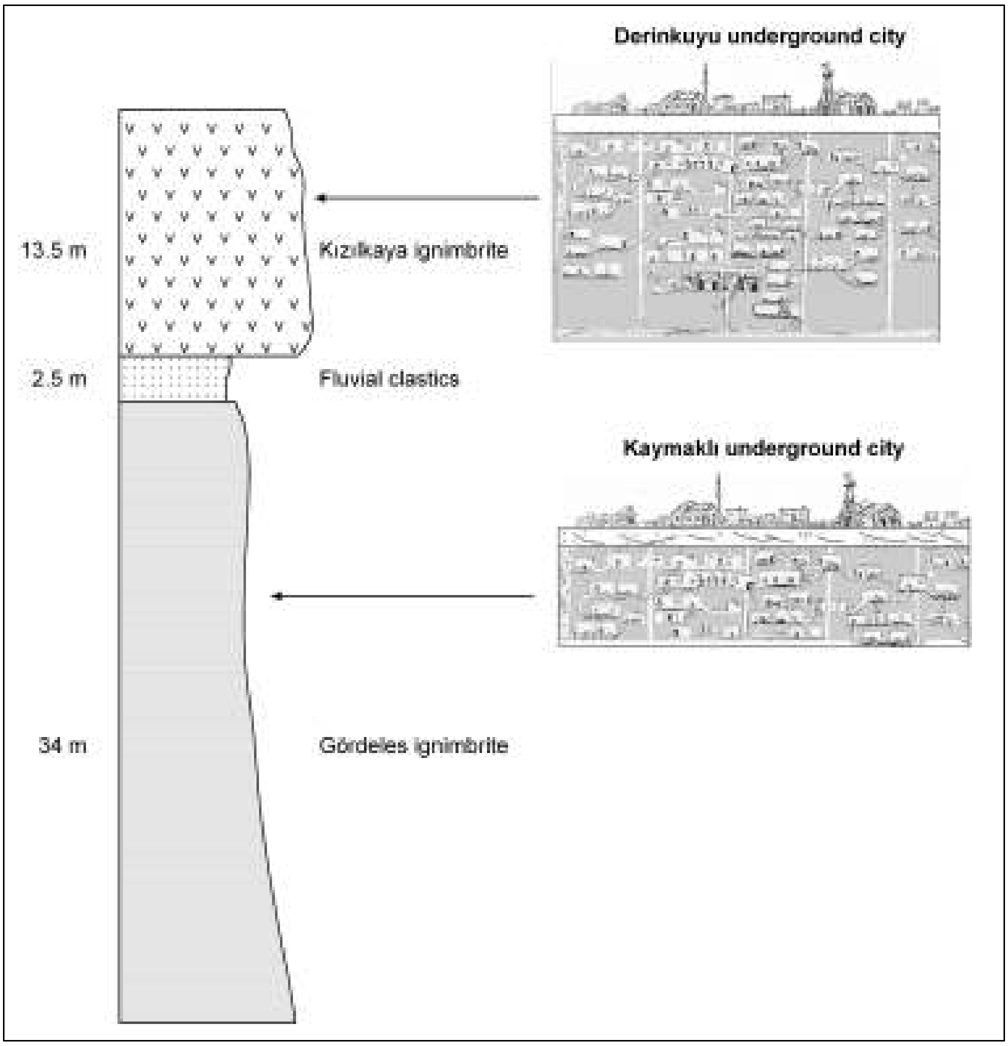

Figure 3.3. Stratigraphic section measured around Çekme village. Sketch cross sections of underground cities are taken from: http://www.avanosevi.com/tr/yeralti%20sehri.html)

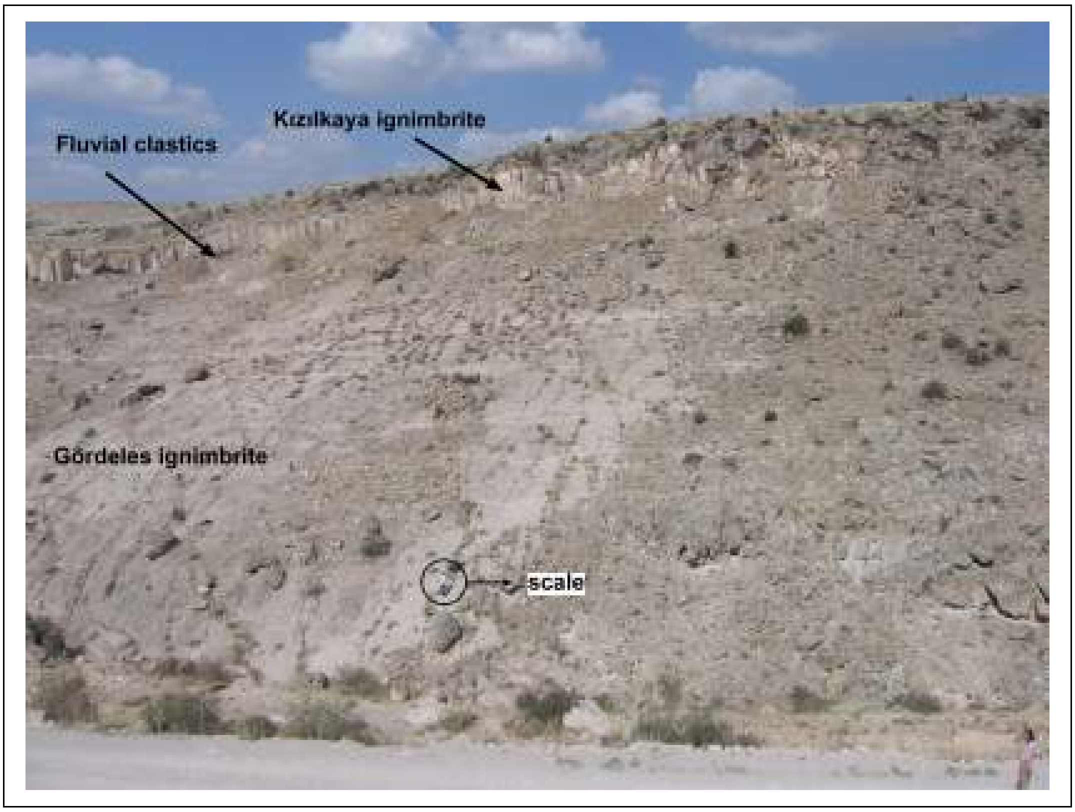

Figure 3.4. Section measured (Figure 3.3) near Çekme village (view to N).

Figure 3.5. Close-up view of fluvial clastics between Kızılkaya and Gördeles ignimbrites. (view to NE).

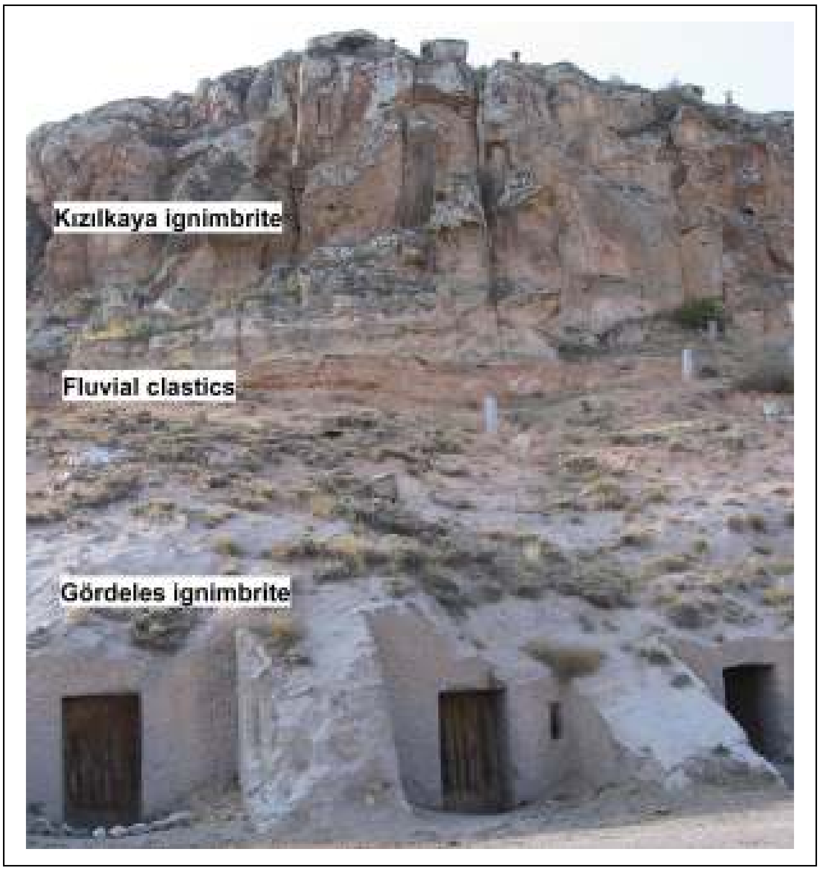

Figure 3.6. Stratigraphic section around Mazıköy (10 km east of Kaymaklı) (view to NW).

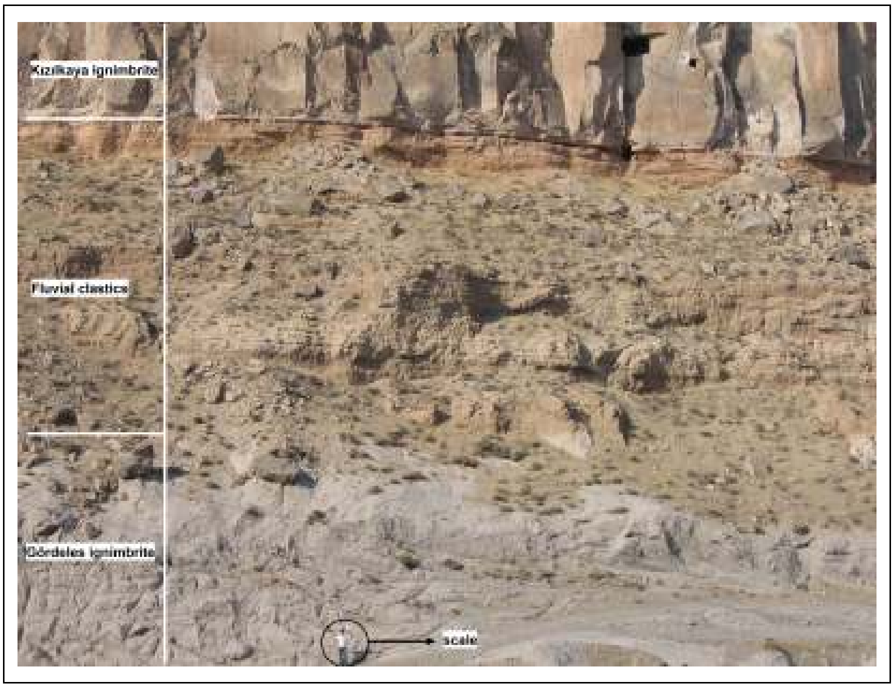

Figure 3.7. Stratigraphic section around Başköy-Güzelöz villages (about 22-23 km east of Derinkuyu) (view to N).

3.3. Geology of Derinkuyu Underground City

Geological map of the area in the close vicinity of Derinkuyu is shown in Figure 3.8. The cross section prepared between Derinkuyu and Çekme village is given in Figure 3.9. The area at the surface around Derinkuyu underground city is covered by a thin deposit of Quaternary alluvium. The thickness of this alluvium is very thin (about 1 m) as observed at the entrance of the underground city.

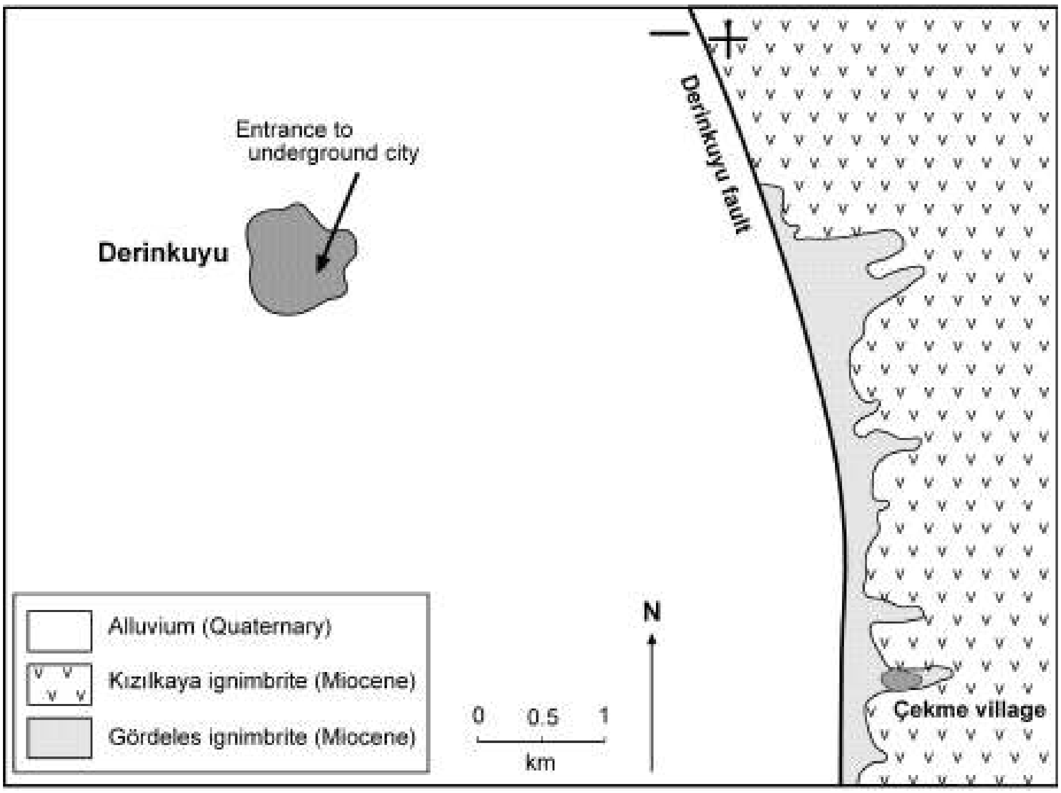

Figure 3.8. Geological map of the area around Derinkuyu

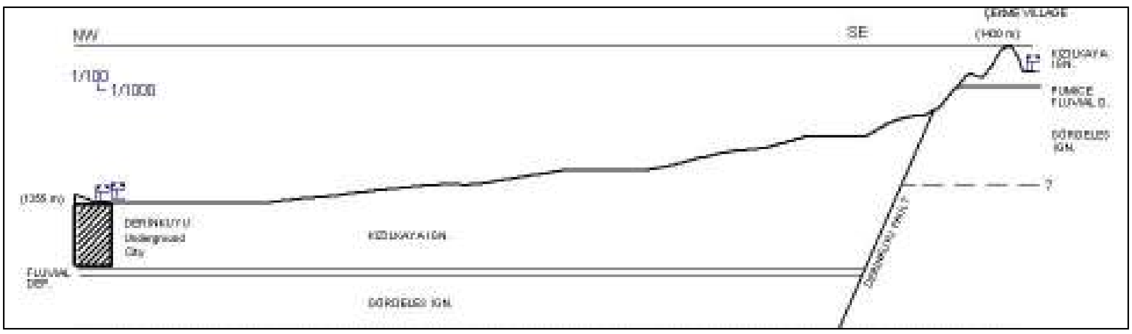

Figure 3.9. Stratigraphic section shows the location of Derinkuyu Underground City in the Ignimbrite Units

Amount of the vertical throw along the fault is estimated as 50 m by Toprak and Kaymakçı (1995). Kızılkaya ignimbrite is used as a rock quarry where regular blocks are provided along the columnar joint surfaces (Figure 3.10).

Figure 3.10. General view of Kızılkaya ignimbrite in the rock quarry around Çekme village (view to N).

Observations made in the underground city indicate that the city is totally carved within Kızılkaya ignimbrite. This observation is approved also in the study made by SIAL (1992) who suggested "İncesu ignimbrite" which is the equivalent of Kızılkaya. The nature of the ignimbrite is consistent almost in all eight floors characterized by welded, light-grey color with a coarse lithic pumice tuff texture. Coarse and fine pumice fragments are commonly observed in the unit.

The first two floors (at the top) of the city are characterized by intense jointing. For this reason, these floors are supported by numerous retaining walls. That is why the joints in these two floors could not be totally measured.

A special attention is given to the presence of fluvial clastic layer that will define the boundary of Kızılkaya and Göreles ignimbrites. However, this unit is believed not to exist in the city suggesting that the whole city is located within Kızılkaya ignimbrite.

There is no reliable data on the depth of the underground city. Different depths are suggested ranging from 40 m to 85 m as described in Chapter 1.3.4. The most probable depth seems to be 40 m as suggested by Gülyaz (1998) which is the depth to the bottom of the city excluding the water shaft (well).

3.4. Geology of Kaymaklı Underground City

Geology of the area around Kaymaklı is given in Figure 3.11. The cross section prepared across the underground city is illustrated in Figure 3.12. The city is carved on the eastern margin of Quaternary alluvium.

The rock units exposed in the area are similar to that of Derinkuyu. The only difference is that several volcanic eruption centers are exposed near Kaymaklı.

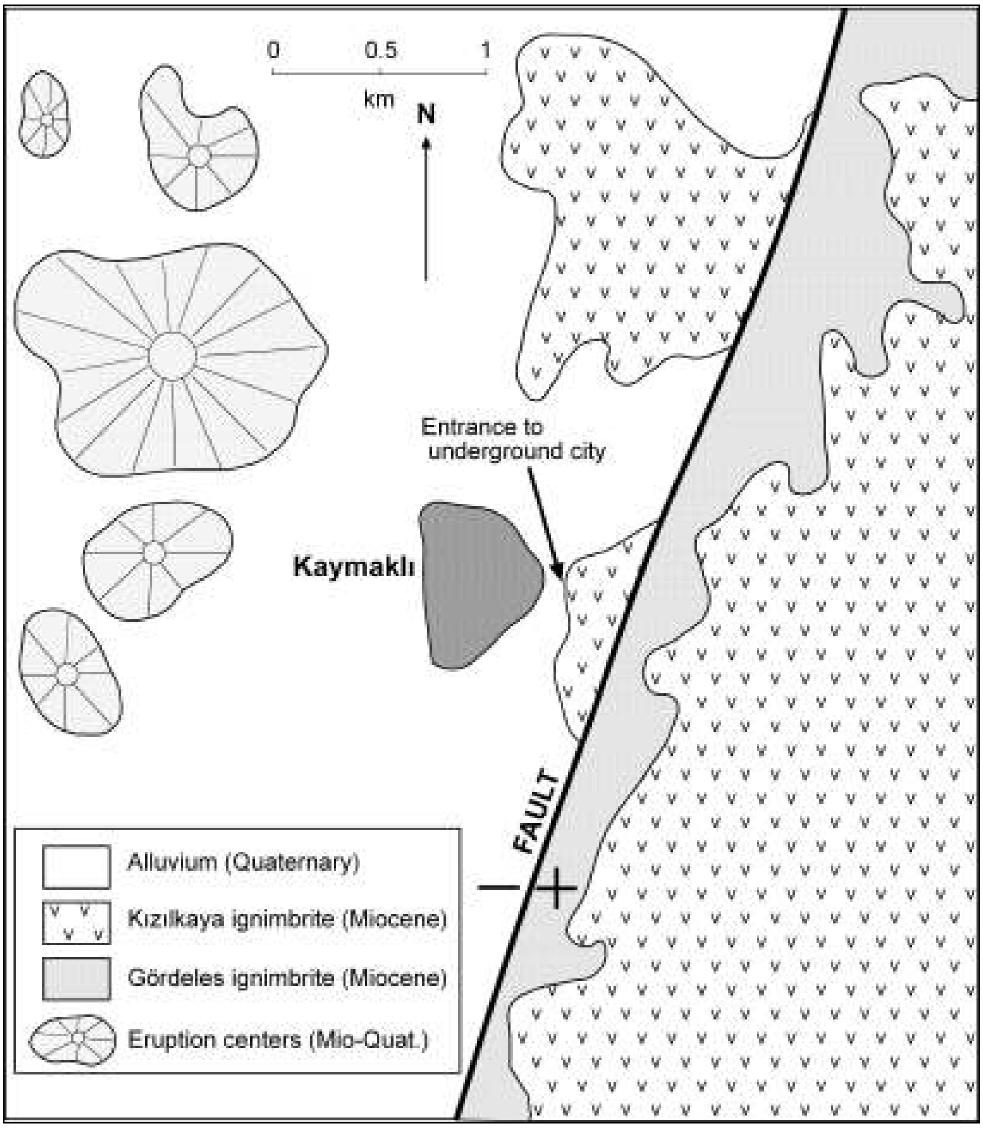

Figure 3.11. Geological map around Kaymaklı

Fluvial clastics that exist between Kızılkaya and Gördeles ignimbrites and behave as a marker bed is well observed in the close vicinity of the Kaymaklı underground city (Figure 3.13). This deposit is observed on the eastern part of the area where the Gördeles ignimbrite is also partly exposed to the surface. Therefore, the field data with no doubt indicate that Kaymaklı underground city is carved within the Gördeles ignimbrite. SIAL (1992), however, claimed that the city is carved within İncesu (Kızılkaya) which is not a correct observation.

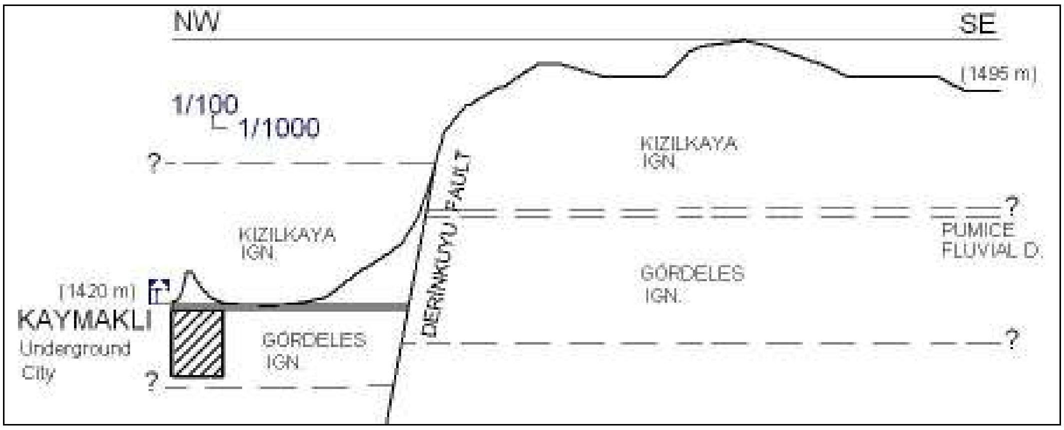

Figure 3.12. Cross section between Kaymaklı and a point 3 km away to SE.

Figure 3.13. Rocks units exposed close to Kaymaklı underground city (view to NE).

Gördeles ignimbrite within the underground city is characterized by white color with gray or pinkish superficial oxidations, homogenous, fine-grained lithology. The texture is consistent in all floors of underground city. Frequency of columnar joints is less than that of Derinkuyu underground city.

All four floors are totally located within the Gördeles ignimbrite; therefore, the bottom of the ignimbrite is not exposed in the city.

There is no available information on the depth of Kaymaklı underground city. Compared with Derinkuyu underground city, the thickness can be estimated approximately as 25 m. The thickness of this ignimbrite measured around Çekme village was determined as 34 m.

CHAPTER IV

DATA AND MEASUREMENTS

In this chapter, method of study and the steps of the applied method are explained. A flowchart of the method is illustrated in Figure 4.1.

4.1. Selection of Sites

Before the collection of data, the first problem was the selection of the site since there are several small and big scale underground settlements in the Cappadocian Region. Two of them -Derinkuyu and Kaymaklı- were selected for the analyses using the criteria listed below:

1- The settlement should be accessible and lightened to measure related data. As already illustrated in Table 1.1 (SIAL, 1992) the number of such settlements is limited and that only certain underground cities can be studied.
2- The settlement should be large to hold enough number of rooms to measure a certain amount of data for statistical purposes. According to Gülyaz and Yenipınar (1996) the number of settlement is 22 as illustrated in Figure 1.2.
3- There should be joints in the settlement to measure. For example, Mazıköy underground city is composed of one floor with almost no jointing.
4- The site should be located in the ignimbrite as this unit is characterized by the presence of cooling joints. Among the visited sites, for example, Mucur underground city is carved into the marble and Acıgöl underground city within the basaltic cinder. Different rock types selected for the underground cities are given in Table 1.1.

After several field trips, the underground cities in Derinkuyu and Kaymaklı are accepted as the most appropriate underground cities to be worked on.

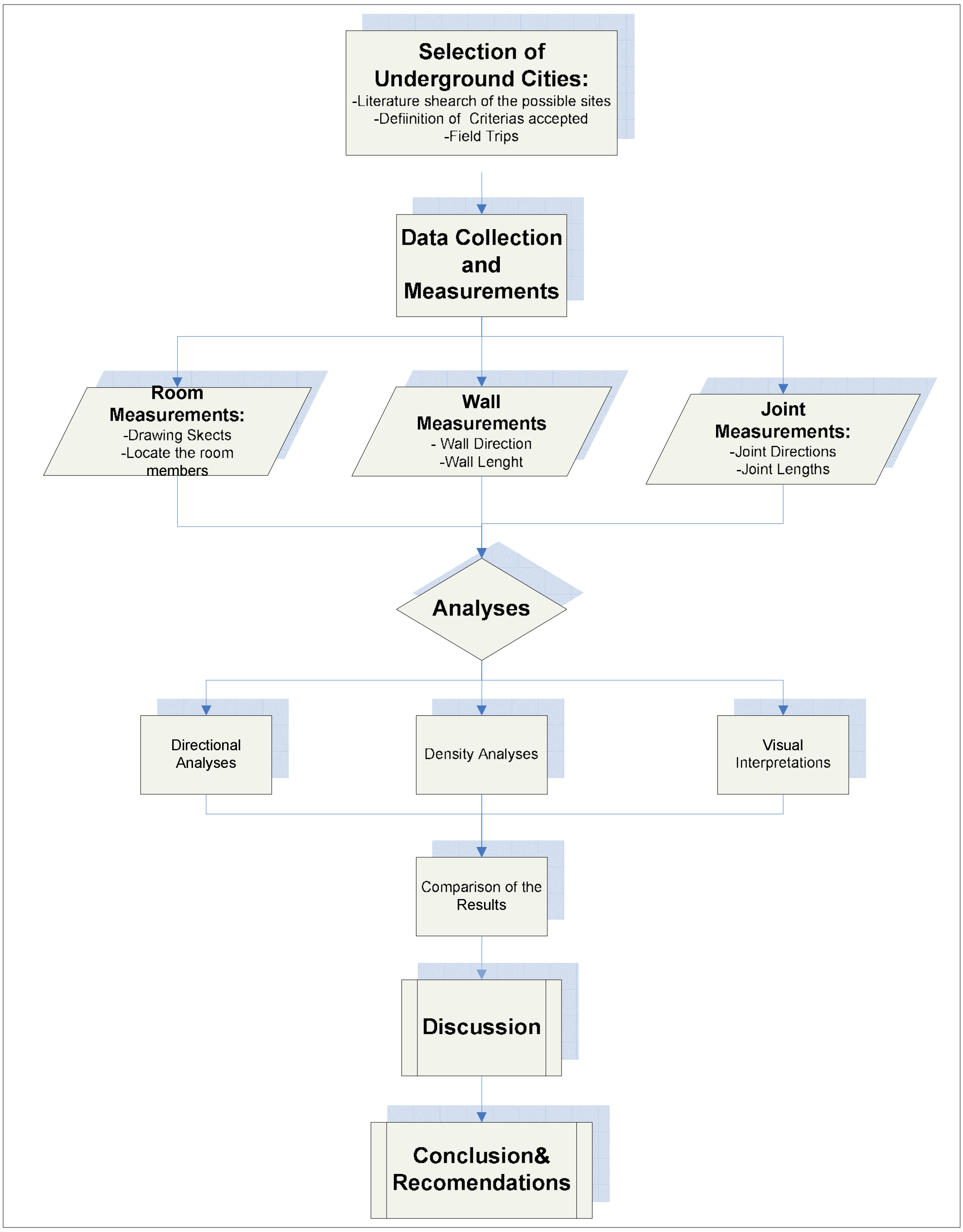

Figure 4.1. Flowchart of the steps followed in the study

4.2. Collection of Data

After the selection of these two settlements for measurement, the sites were visited to collect data. Four sets of data are obtained during these visits. The first three sets are measured in the underground city, while the last one in the field.

1- **Room Measurements:** There are no available architectural drawings of the underground settlements of Cappadocian region. The first difficulty, therefore, is the plan of the rooms in which walls and joints will be measured. For this reason the first step is to identify the rooms and prepare sketch maps for them. Each room is given a unique number in order to make it possible to build a relationship between the room and wall/joint database. The numbers are assigned beginning from the ground floor to the top floor.

2- **Wall Measurements:** Direction and length of the walls are measured by using compass and steel tape. There are relatively few straight walls forming rectangular rooms. Because many of the walls do not have an exact straight direction, an average trend direction for each wall is taken into account. Generally, the rooms have trapezoid shapes and curved walls. For the curved walls, radii of the curves are measured.

3- **Joint Measurements:** All joints detected in the rooms are measured. Positions of the joints are drawn to locate them in the room in order to define their relations with the corners, pillars, walls and exits of the rooms. Directions of the joints are measured by using quadrant method. Amount of the dip is not considered in this study as most of the joints are almost vertical. In some cases, the same joint cuts across different rooms, which is measured and drawn separately for each room.

4- **Field Measurements:** Field data measured from the joints are important in order to make a comparison of the joints measured in the underground city. For this reason a suitable place looked for to measure the joints in the field. Çekme village which is situated 5.5 km southeast of Derinkuyu underground city is the nearest the most appropriate site where necessary measurements can be taken. This site also provides a good stratigraphic section where the ignimbrites used in this study are exposed. The details of the measurements at this site will be given in Section 4.4.

The measurements are illustrated in four tables in the appendices. The general views of the floors and the rooms are illustrated in Appendix A for Derinkuyu and Appendix B for Kaymaklı.

Room measurements that contain floor number, room number, wall name, wall directions, wall lengths, joint names and joint directions of Derinkuyu and Kaymaklı underground cities are illustrated in Appendix C and Appendix D, respectively.

Floor number, room number, room area, joint length and joint density values are given in Appendix E and Appendix F for Derinkuyu and Kaymaklı underground cities, respectively.

Joint density data including number of joints and total length of room axes are given in Appendix G and Appendix H for Derinkuyu and Kaymaklı underground cities, respectively.

The field measurements for Kızılkaya and Gördeles Ignimbrite are illustrated in Appendices I and J, respectively.

4.3. Measurements at Derinkuyu Underground City

Derinkuyu underground city is situated between Niğde and Nevşehir, about 29 km to Nevşehir and 9 km to Kaymaklı. Derinkuyu underground city is settled in the modern Derinkuyu, a town of Nevşehir, which is one the most famous touristic sites of Cappadocia visited by thousands of people in a single day.

In Derinkuyu underground city 46 rooms are measured within 7 floors. The floors and the rooms that have access constitute only a certain part of the whole underground city. There are lots of rooms that have collapsed in the course of time and some entrances to other sections of the city are close at present due to danger of collapse.

Diagrams showing the plan views of the rooms are illustrated in Figures 4.2 to 4.6. By the help of these diagrams, following observations can be obtained about rooms:

- There are seven floors in the city; however, the floor concept here is different from how it is used today. The main reasons for this difference are: 1) the floors do not have definite boundaries and are not exactly placed under the upper floor; 2) vertical distances between the floors can change from place to place.
- There are eight rooms in the first floor (top floor), five rooms in the second floor, six rooms in the third floor, twelve rooms in the fourth floor, five rooms in the fifth floor, three rooms in the sixth floor, six rooms in the seventh floor and one room in the eighth floor (ground floor) (Appendix A).
- Heights and shapes of the rooms are not similar to each other. Some of the rooms are very small and short in height, but there are some big areas that look like a hall or a square of the floor.
- There are 24 rectangular rooms while the others are circular, elliptical or polygonal in shape.
- The minimum room area is 1.6 m^2 (Room 23) and the maximum room area is 63.8 m^2 (Room 6).
- Total room area in Derinkuyu underground city is 539.7 m^2, and the average room area is 11.7 m^2. Average room areas of the floors from top to ground are 17.7, 21.2, 6.9, 5.4, 8.4, 6.4, 29.4 and 6.4 respectively.
- In two rooms, rectangular columns (pillars) are observed, one of them controls the room entrance and the others are situated in the middle of the room (Room no: 4 and 9).

Joints measured in the rooms show different directions and frequency. The visual interpretations about the joints in the rooms are as follows:

- The number of joints observed in the first floor is nineteen, for the second floor it is seven, for the third floor it is thirteen, for the fourth floor it is twenty two, for the fifth floor it is nine, for the sixth floor it is 2, for the seventh floor it is thirty and for the eighth floor it is two.
- Total length of joints in the rooms is 321.1 m.
- In 3 rooms (out of 46) no joint is detected (room no: 10, 12, 37).

- In 12 rooms only one joint is detected per room.
- In 17 rooms two joints are detected per room.
- In 14 rooms there are three or more than three joints. The maximum number of joints is eleven in the room 6.
- In 5 rooms the joints are nearly tangential to the corners (room no: 3, 7, 8, 13, 23).
- In the room 20, one of the joints is nearly parallel to the entrance of the room and the entrance is controlled by this joint.
- 5 walls of 5 rooms are fully controlled by the joints (room no: 2, 6, 26, 32 and 43).
- In 10 rooms the joint intersects with the corners of the rooms (room no: 1, 6, 16, 18, 26, 28, 30, 35, 40, 46).
- In the room 44, the joint touches to the corners of the room.
- Three of the four pillars are controlled by the joints in two rooms (room no: 4 and 9). One of the joints is parallel to one side of the pillar and two of them touch diagonal to the pillar.
- There is no specific joint pattern due to the room geometries.

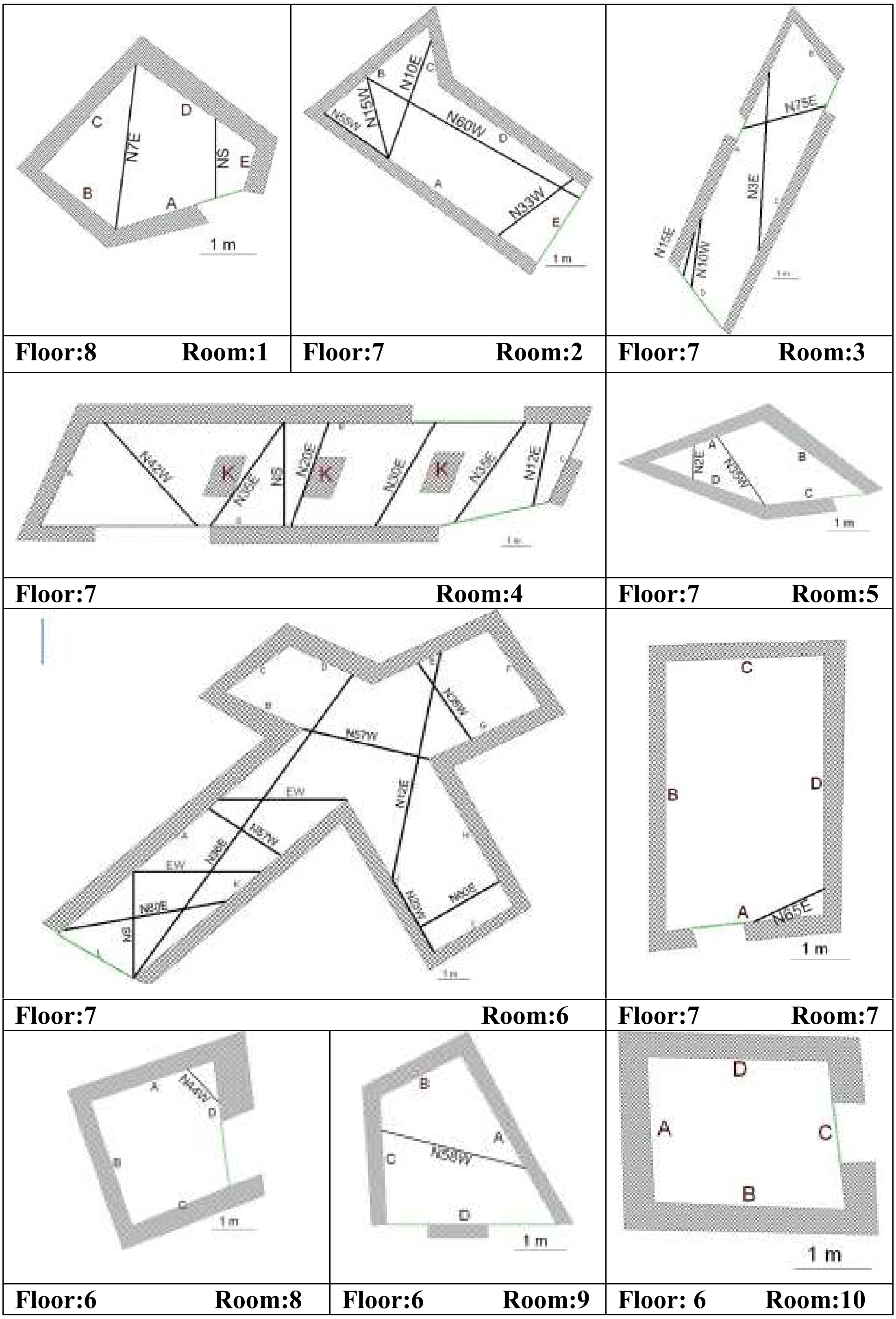

Figure 4.2. Plan views of rooms, from 1 to 10, measured in Derinkuyu Underground City. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

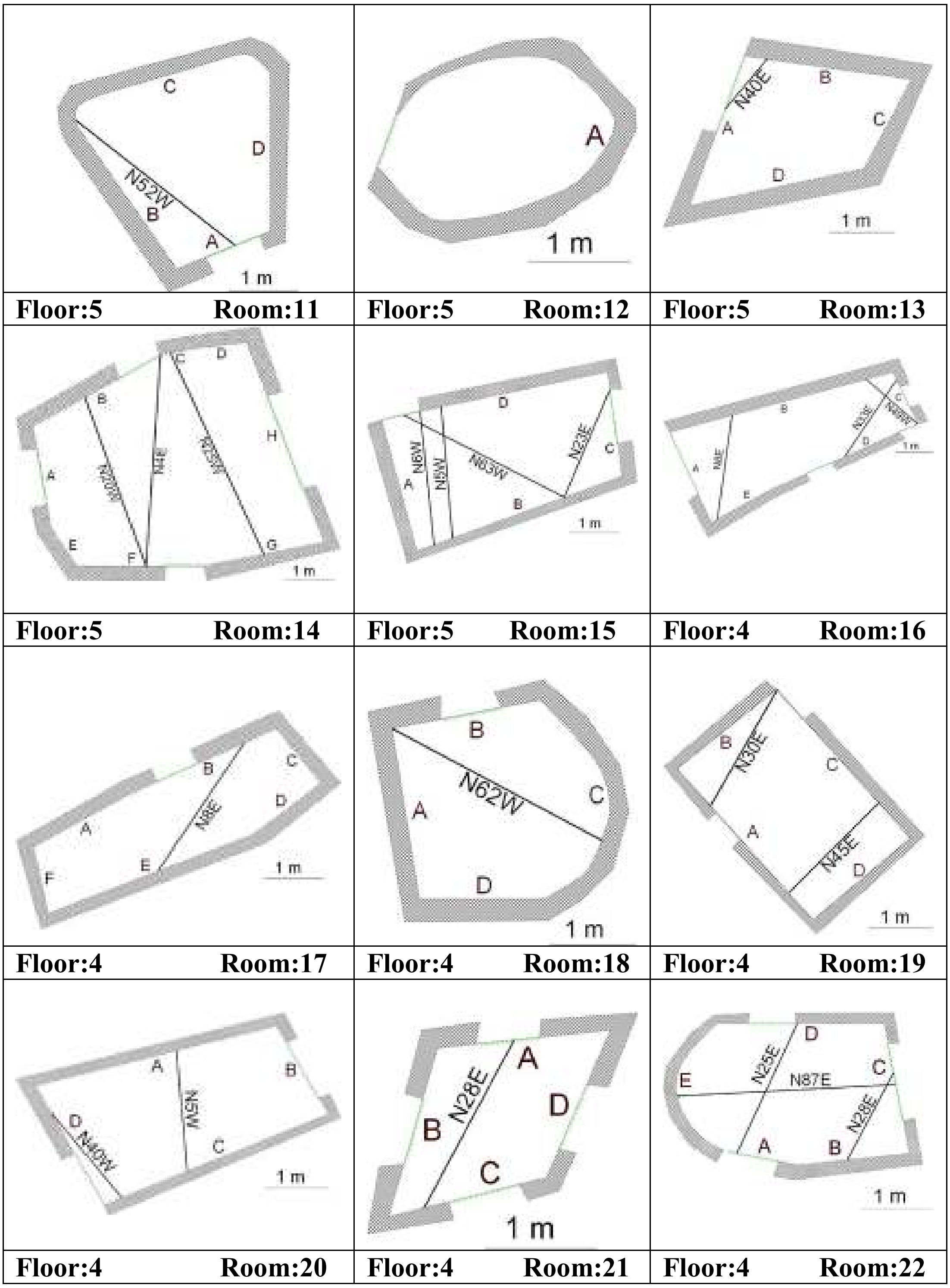

Figure 4.3. Plan views of rooms, from 11 to 22, measured in Derinkuyu underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

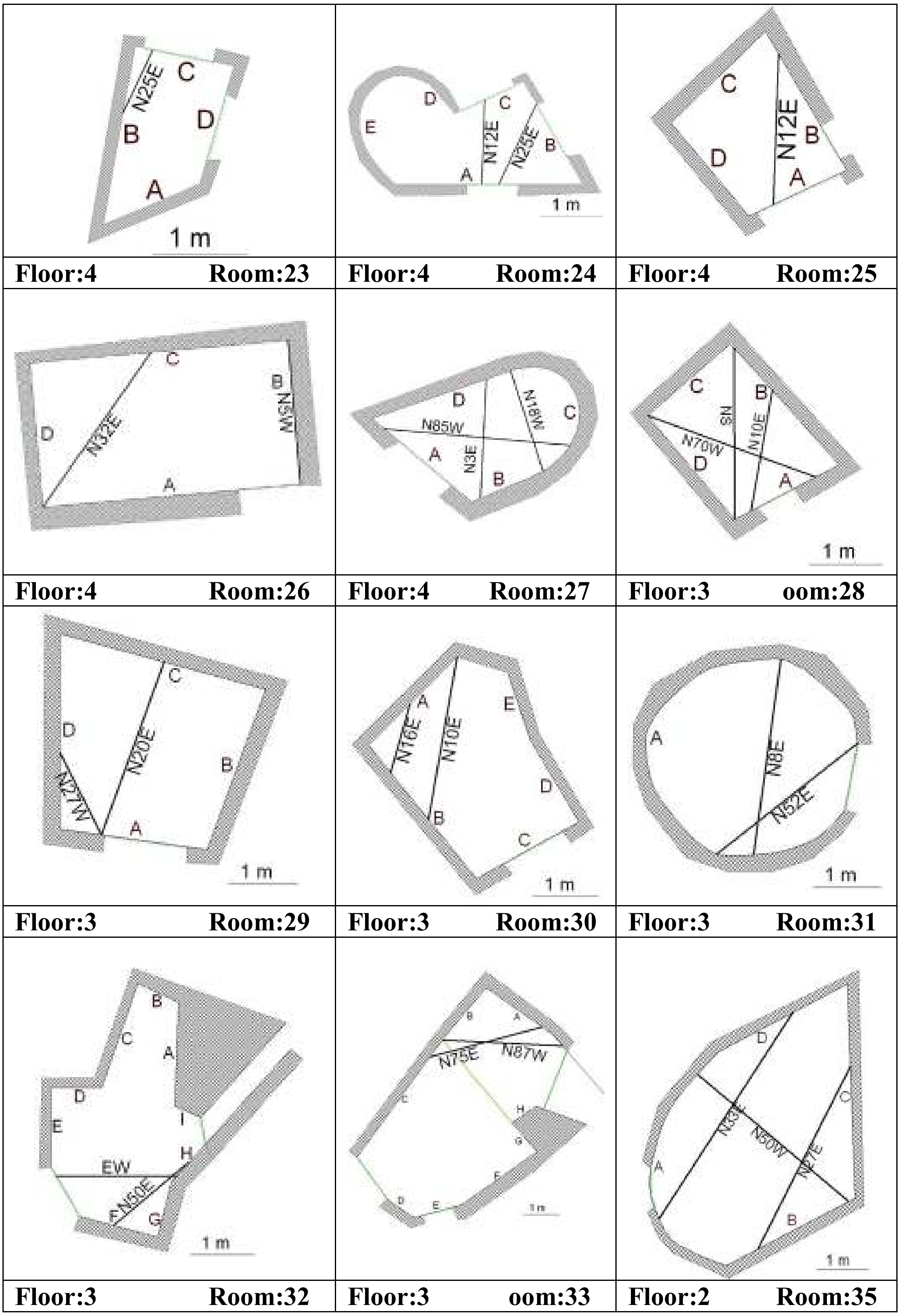

Figure 4.4. Plan views of rooms, from 23 to 35, measured in Derinkuyu underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

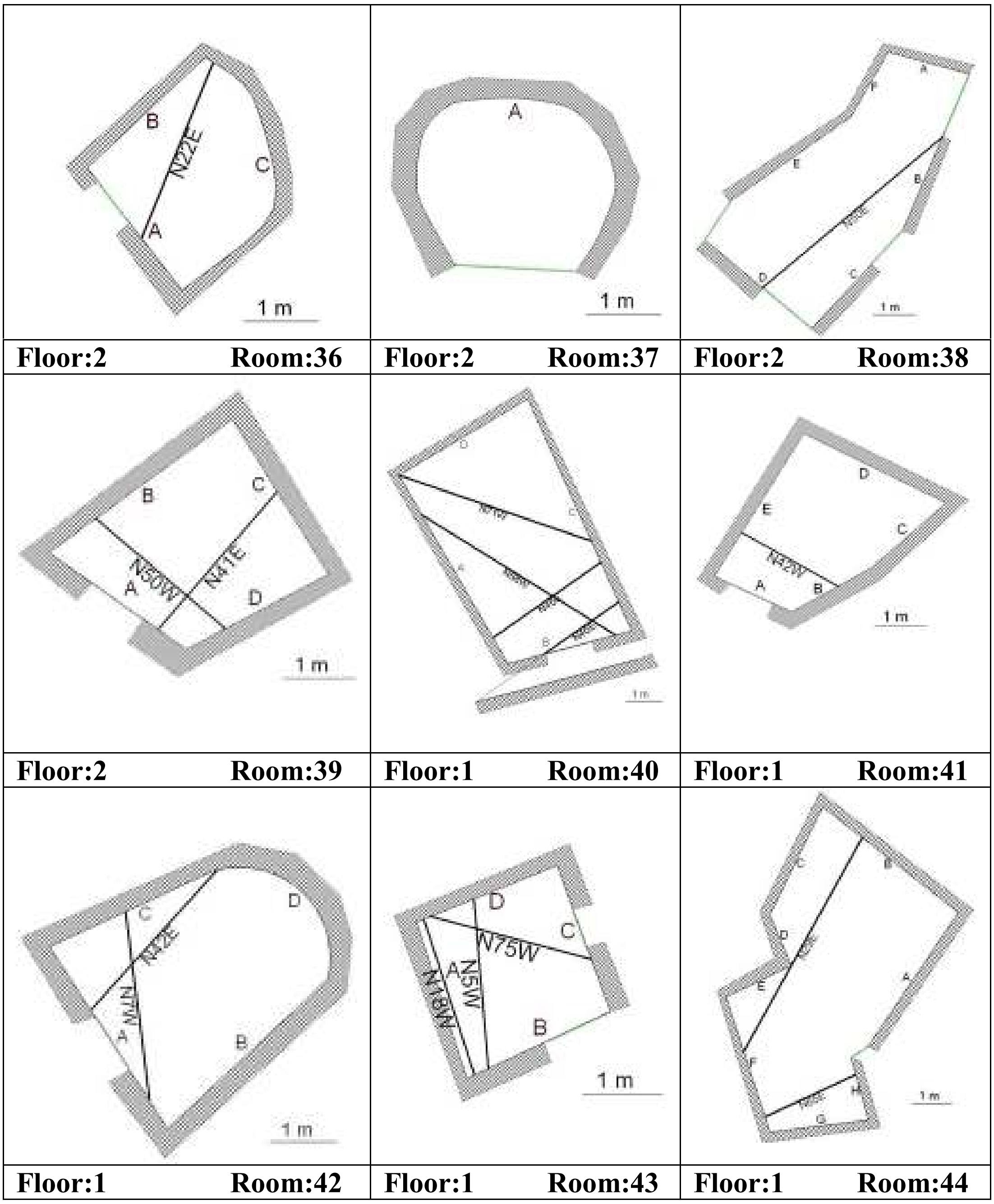

Figure 4.5. Plan views of rooms, from 36 to 44, measured in Derinkuyu underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

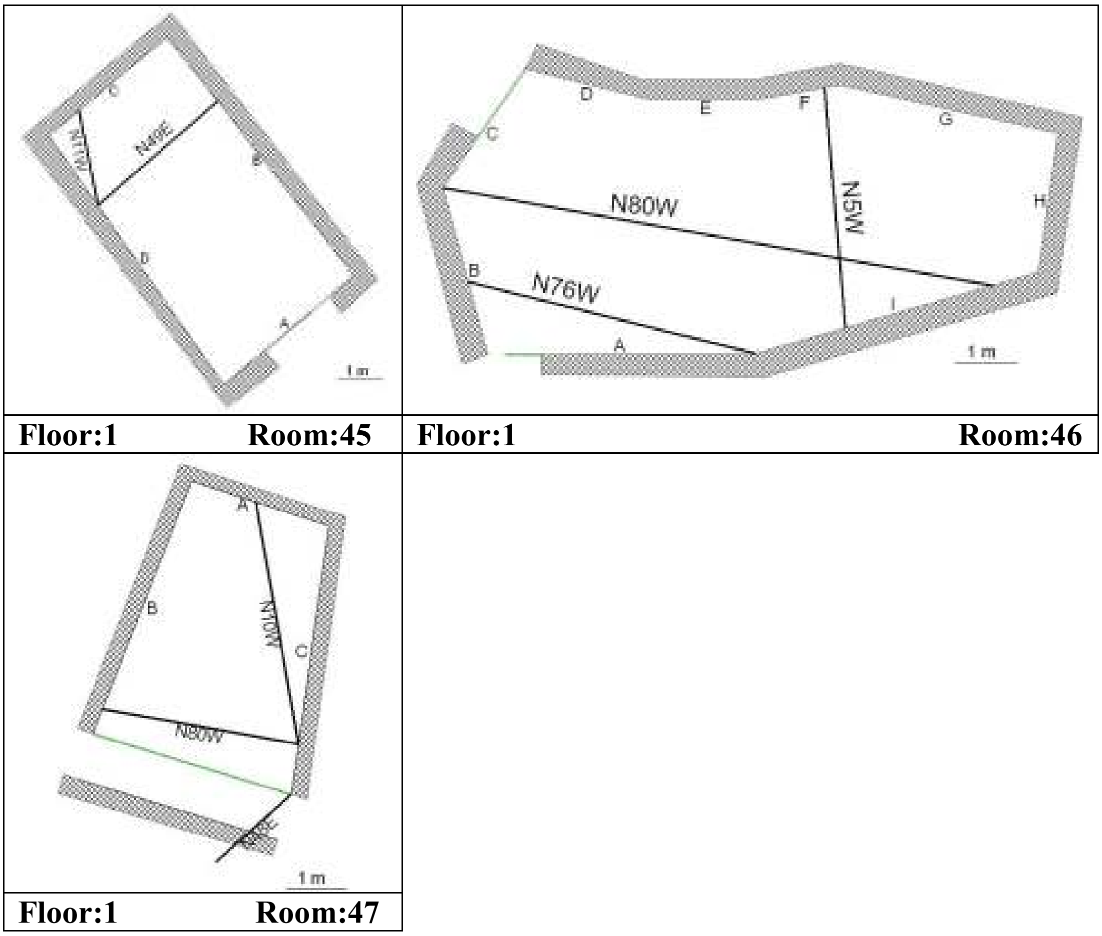

Figure 4.6. Plan views of rooms, from 45 to 47, measured in Derinkuyu underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

4.4. Measurements at Kaymaklı Underground City

Kaymaklı is situated between Niğde and Nevşehir, about 20 km to Nevşehir and 9 km to Derinkuyu. Kaymaklı underground city is settled in the modern town Kaymaklı which is a very famous town attracting many tourists from all over the world to Cappadocia.

While taking the measurements at Kaymaklı underground city, 64 rooms are identified in a total of 4 floors. There are lots of rooms that have no access in the site because of the collapses at certain sections.

Diagrams showing plan views of the rooms measured in Kaymaklı underground settlements are illustrated in Figures 4.7, 4.8, 4.9, 4.10, 4.11, 4.12. North is the top of the paper in all diagrams. By examining these diagrams, following observations can be made:

- Rooms are situated like honeycombs, and the floors are spread on a flat area.
- There are six rooms in the first floor (top floor), twenty eight rooms in the second floor, fourteen rooms in the third floor and sixteen rooms in the fourth floor (ground floor) (Appendix B).
- Heights and shapes of the rooms are not similar to each other. Some of the rooms are very small and short in height while there are some big areas that look like a hall or a square of the floor.
- There are 28 rectangular rooms while others are circular, elliptical or polygonal in shape.
- The minimum room area is 2.4 m^2 (room 39) and the maximum room area is 35.3 m^2 (room 60).
- At the doors to three rooms, rectangular columns (pillars) were identified (room no: 25, 37, 59).

Joints measured in the rooms show different directions and frequency. It is important to note that there is no joint in ten rooms in the 4th floor. The detected N-S direction joint in six rooms of the 4th floor and one room of the 3rd floor is the same joint. Other observations about the joints in the rooms are:

- The number of joints observed in the first floor is five, it is twenty for the second floor, twenty four for the third floor, and seven for the fourth floor.
- Total length of joints in the rooms is 150.7 m.
- Total number of rooms is 64 and in 22 rooms no joints are detected.
- In 30 rooms only one joint is detected.
- In 10 rooms two joints are detected.
- The maximum number of joints is three in two rooms (rooms 55 and 37).
- In four rooms the joint is nearly tangential to the corners (room no: 13, 34, 48, 58).

- In the room 54, the joint is parallel to the entrance and the entrance is controlled by this joint.
- Three walls of three rooms are fully controlled by the joints (room no: 27, 42 and 57).
- In ten rooms the joint intersects with the corner of the rooms (room no: 60, 58, 45, 44, 41, 36, 24, 20, 15, 14).
- In three rooms, the joints are tangential or nearly touching to the corners of the rooms (room no: 15, 21 and 55).
- There is no specific joint pattern as to the room geometries.
- There are no joints controlling the pillars in the rooms.

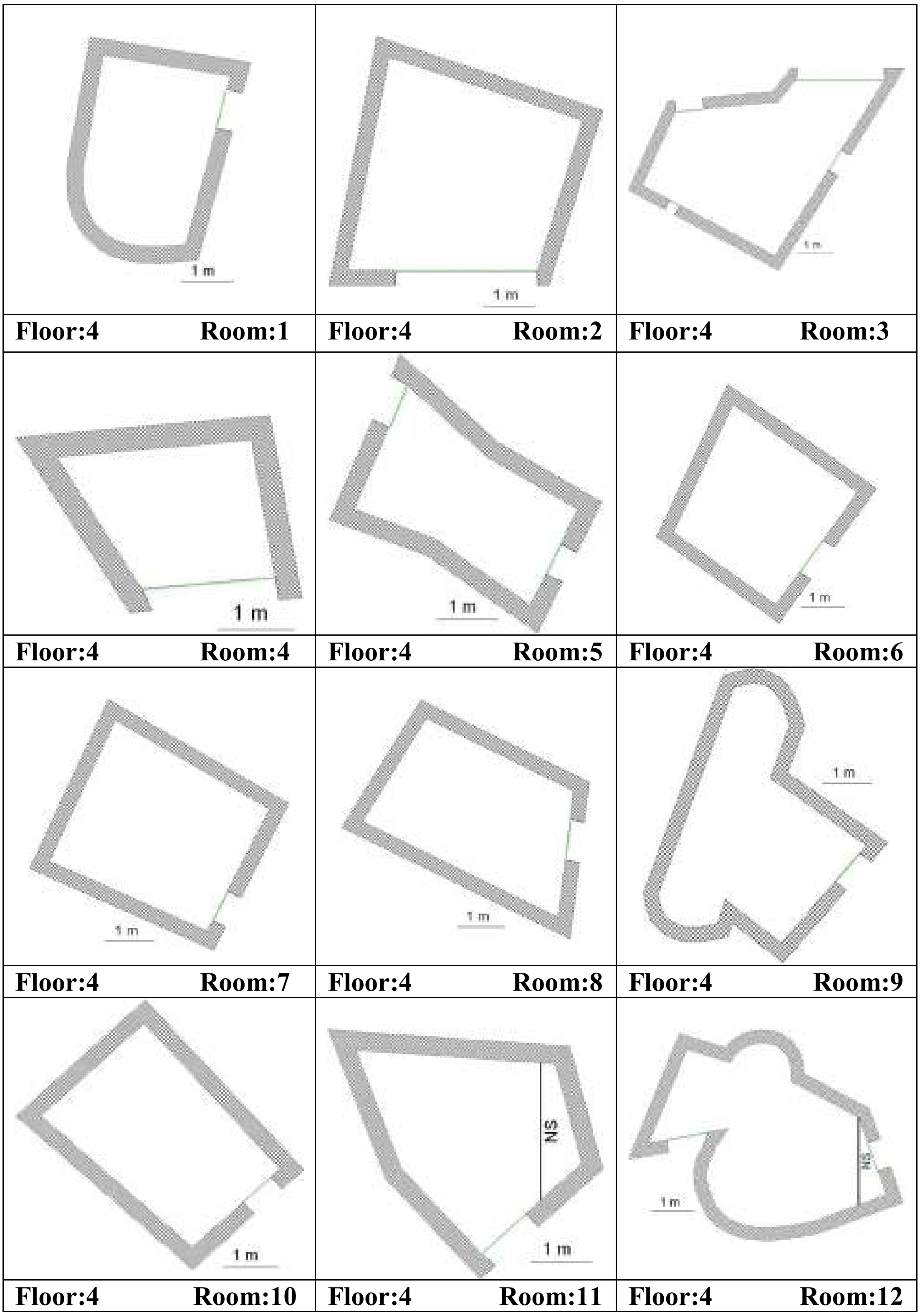

Figure 4.7. Plan views of rooms, from 1 to 12, measured in Kaymaklı underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

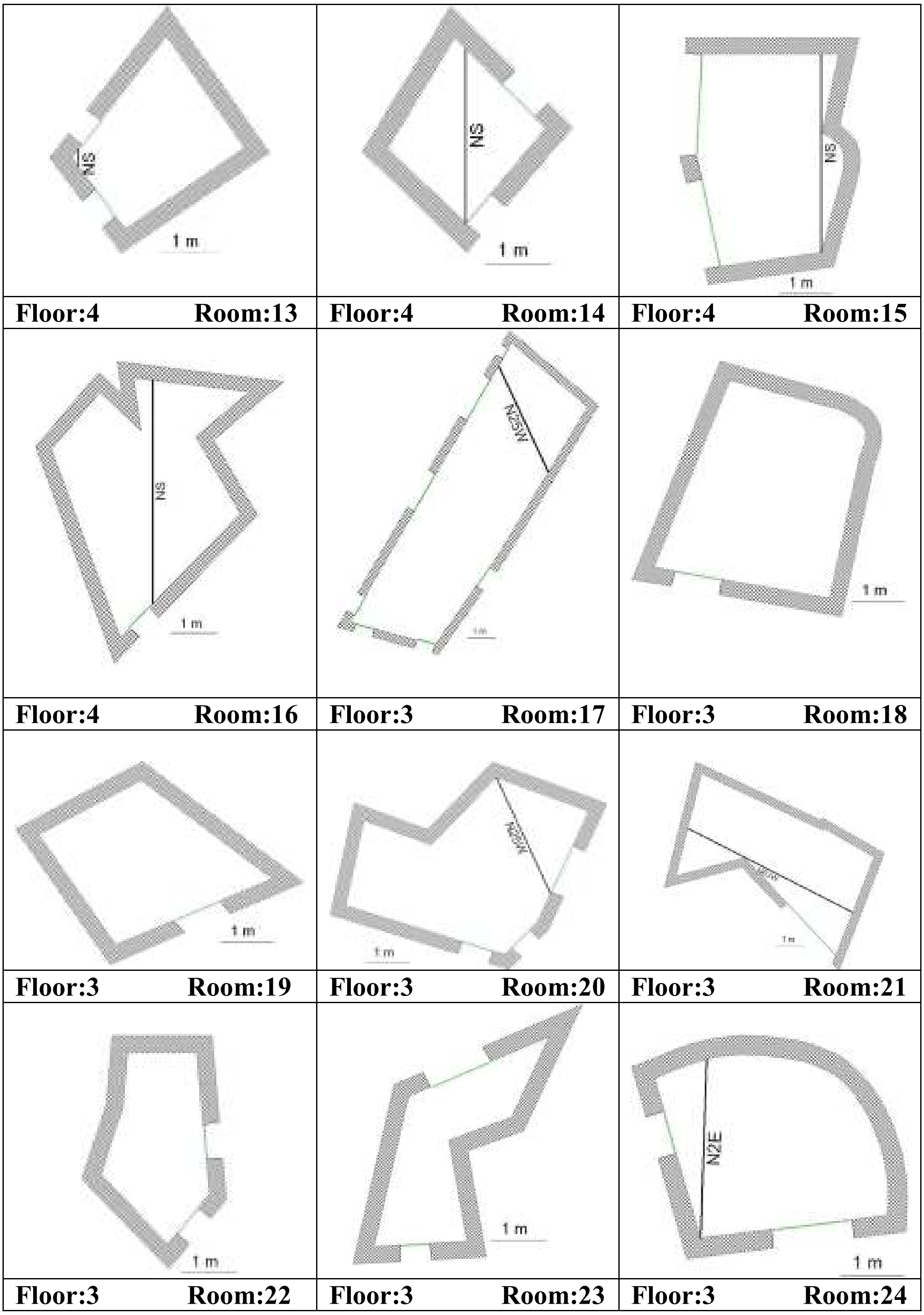

Figure 4.8. Plan views of rooms, from 13 to 24, measured in Kaymaklı underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

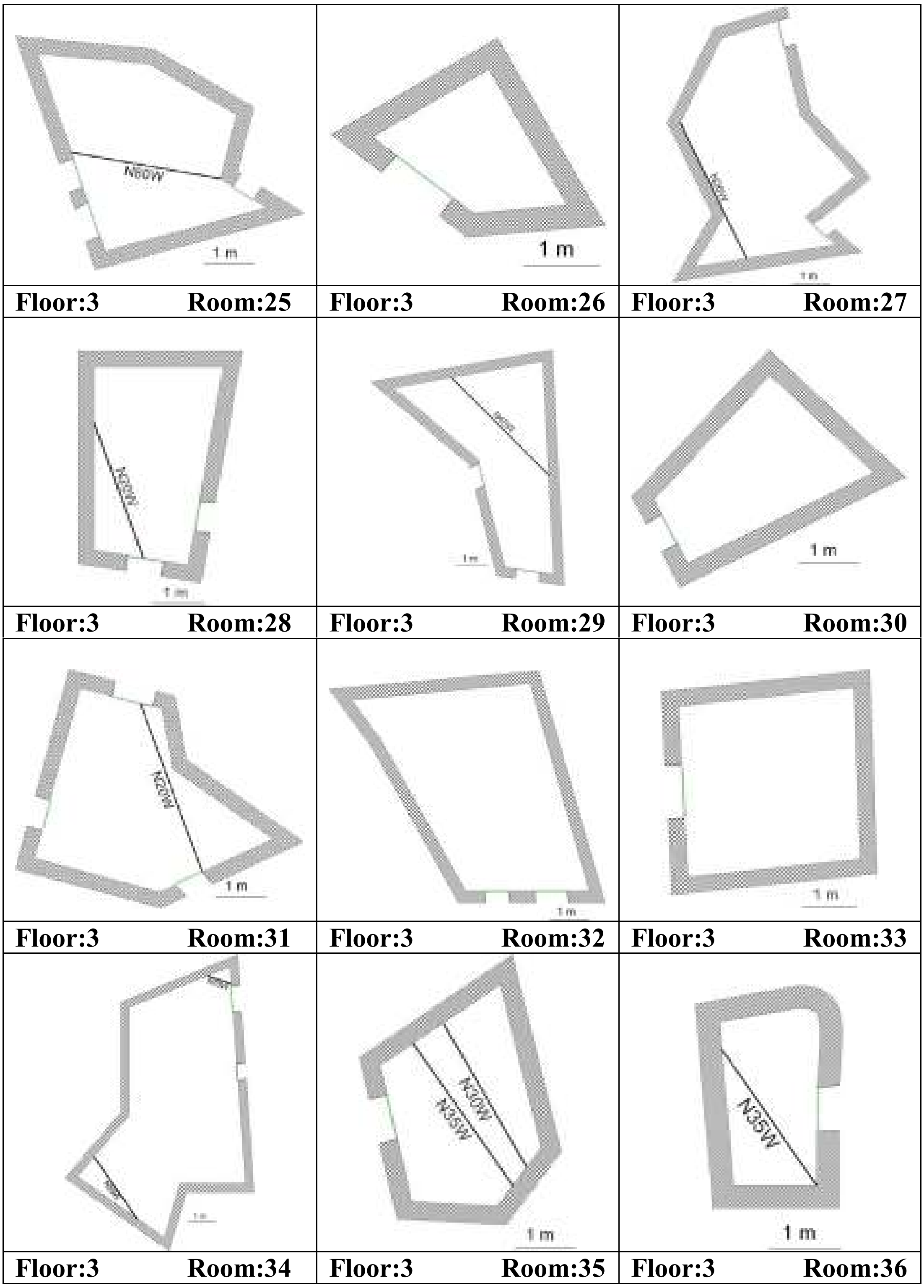

Figure 4.9. Plan views of rooms, from 25 to 36, measured in Kaymaklı underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

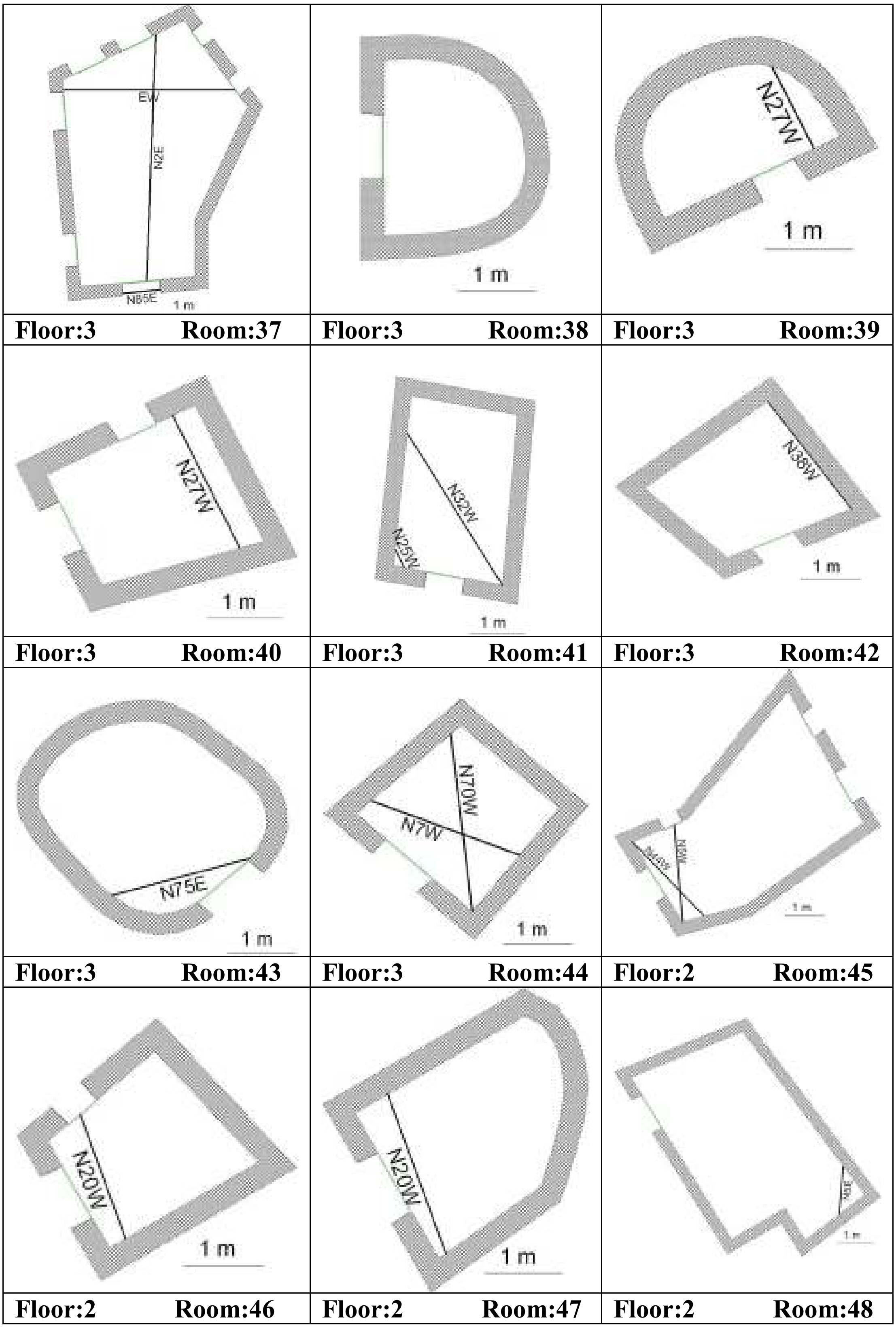

Figure 4.10. Plan views of rooms, from 37 to 48, measured in Kaymaklı underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

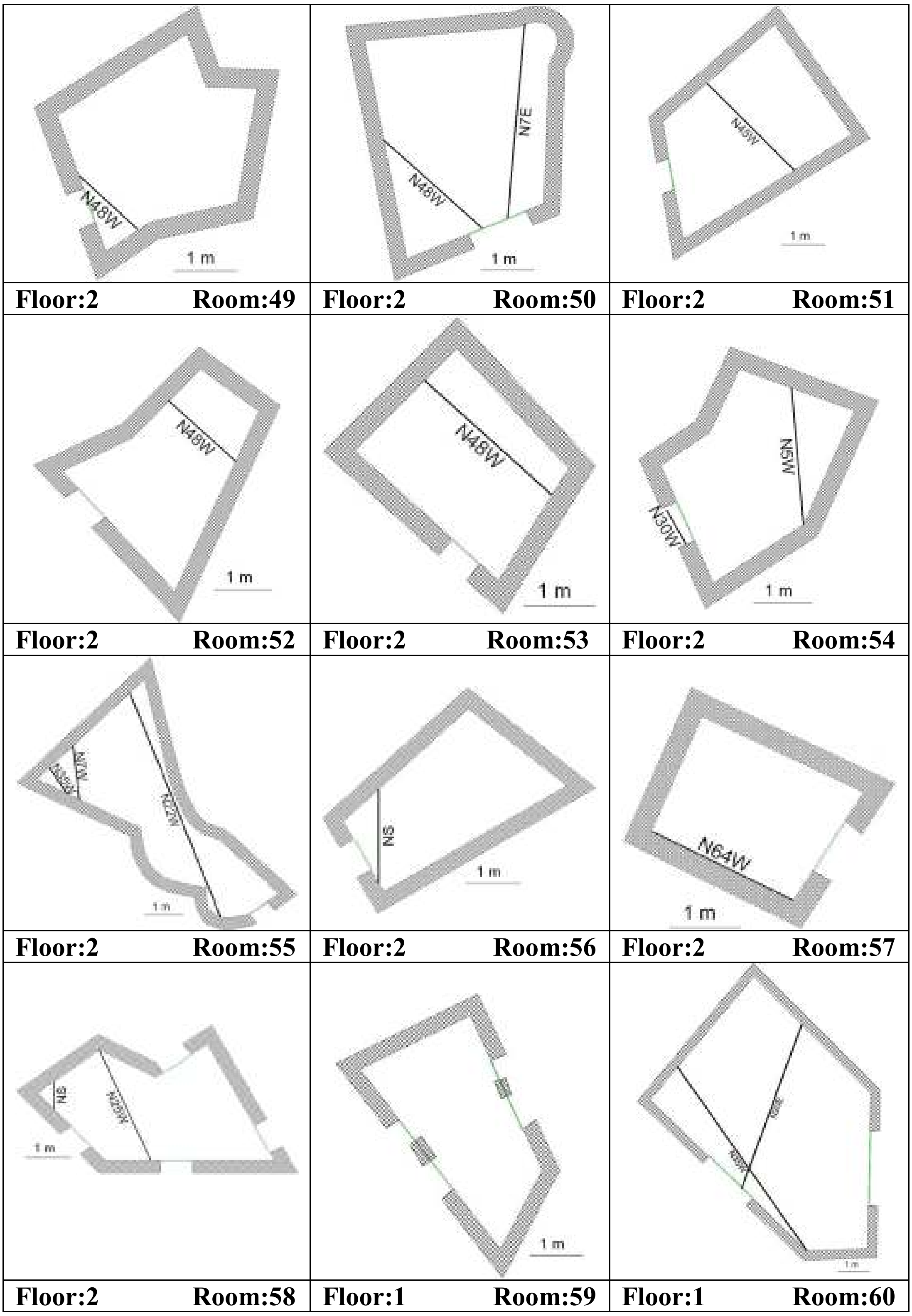

Figure 4.11. Plan views of rooms, from 49 to 60, measured in Kaymaklı underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

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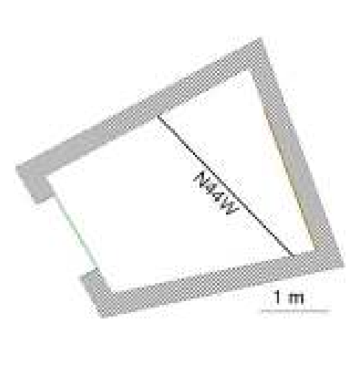
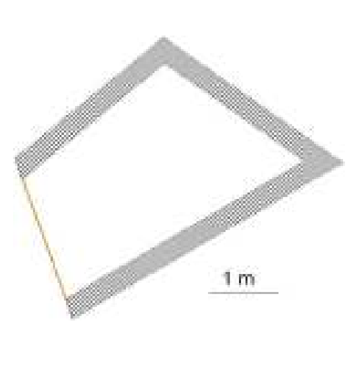
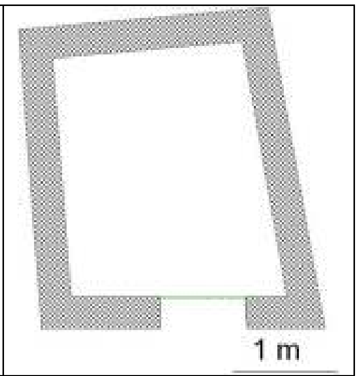
<td></td>
<td></td>
<td></td>
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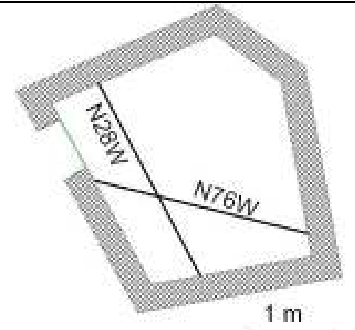
<td></td>
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Figure 4.12. Plan views of rooms, from 61 to 64, measured in Kaymaklı underground city. The black lines show the joints with their directions. The letters refer to the wall segments. The green, thin lines indicate the entrances of the rooms and the orange dashed lines indicate the collapsed walls. North is top of sketch in all.

4.5. Field Measurements

Since the Derinkuyu underground city was carved in the Kızılkaya and Kaymaklı underground city was carved in the Gördeles ignimbrite, the field survey should be carried out in the area here these ignimbrites are exposed. Several reconnaissance trips are made to find suitable place(s).

Derinkuyu underground city is located within the Derinkuyu basin; therefore, Quaternary alluvial deposits are exposed to the surface. The nearest outcrops of the ignimbrites are located to the east of the site around the Derinkuyu fault where the ignimbrites are exposed over the upthrown block of the fault. Çekme village (an abandoned settlement) is the best place because:

- Both Kızılkaya and Gördeles ignimbrites are exposed and the stratigraphy of the sequences is clear here,
- There are ancient rock quarries in Kızılkaya ignimbrites close the village. Therefore, good surfaces to measure the joints exist in this site.
- About 30 m of Gördeles ignimbrite is exposed to the surface which is almost a unique site in the region to study the Gördeles ignimbrite.

A second site is looked for in the vicinity of Kaymaklı underground city, however, a suitable location is not found. The difficulty for this site is that the Gördeles ignimbrite is not exposed or is exposed at a large distance (e.g. more than 10 km).

This area is situated on the upward block of the Derinkuyu Fault and the outcrops of the both Ignimbrite and the fluvial deposits between two units can be detected easily. In the study area the maximum measured height of Kızılkaya ignimbrite is 13.7 meters. The Kızılkaya joints are measured in an abandoned rock quarry near Çekme village. In this quarry the height of the Kızılkaya is 7.5 meters (Figure 4.13). Since there is no outcrop of ignimbrite appropriate to measure around Kaymaklı underground city, the joint of the Gördeles Ignimbrite are measured in this area. The measurement of different units in the same area is also an advantage, according to the same affect of the tectonic settings on both ignimbrites.

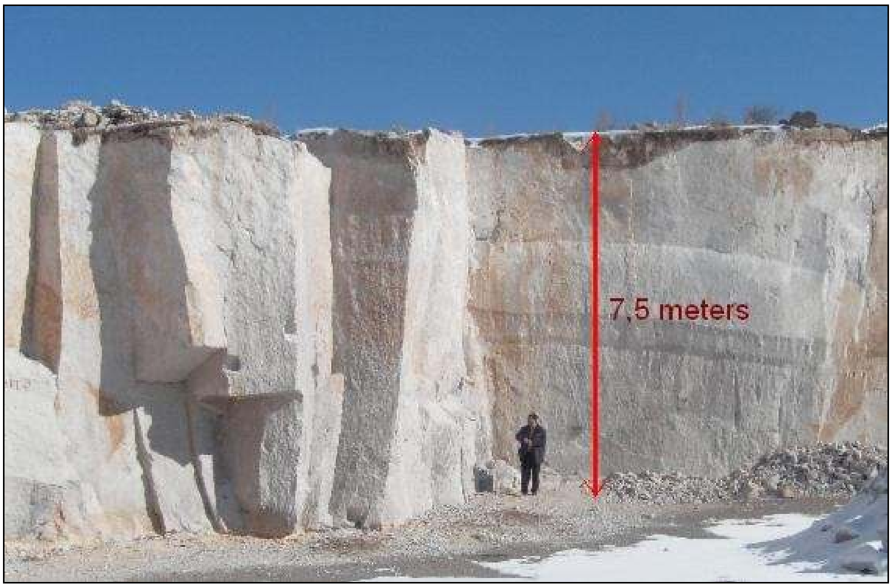


Figure 4.13. Measurements of the Kızılkaya Ignimbrite in Çekme Village (view to E).

The talus of the Kızılkaya, soil and vegetation cover the Gördeles Ignimbrite just about whole surface, but the houses of the village were built on the Gördeles unit. So the joints can be detected and measured on the roads of the village, but the height of the Gördeles can not be measured (Figure 4.14).

Figure 4.14. Measurements of the Gördeles Ignimbrite in Çekme Village (view to NE).

In the Kızılkaya measurement, the joints are measured by using the side walls of the rock and in Gördeles measurements are carried out at the top of Ignimbrite layer. The maximum distances that can walk through on the field are taken as one measurement line and the joints cut this line are measured. The first set of the measurements is illustrated in Figure 4.15.

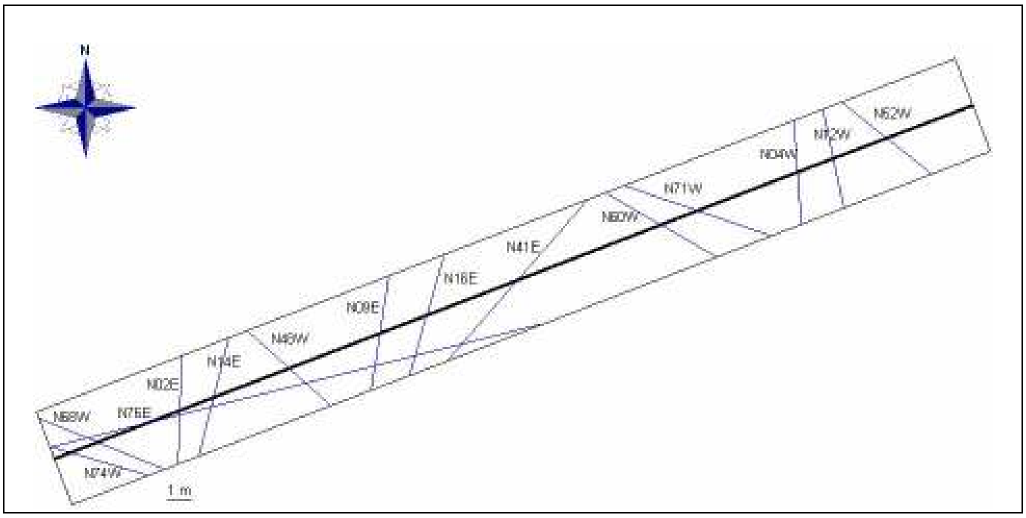


Figure 4.15. One set of joint pattern of Gördeles Ignimbrite.

A Total number of 50 joints are measured in Kızılkaya and of 51 joints in Gördeles Ignimbrite. 4 separate measurement lines used for both ignimbrites. Total length of the measurement lines are 80.1 m for Kızılkaya and 120.3 m for Gördeles (Appendices G and H).

CHAPTER V

ANALYSIS

In this chapter, the analyses performed by using the data collected from the field are presented. Two analyses are carried out. These are directional analysis and density analysis. In the directional analysis, directions of rooms and the joints are used to obtain rose diagrams. In the density analysis, the floor densities of the cities are compared and the cities are also compared among themselves. The other part of the density analysis is to plot scatter graphics of room areas versus joint lengths.

5.1. Directional Analyses

The data of directions at the underground cities are analyzed according to their strikes by using rose diagrams. For this analysis, the acute angles between the joints and the walls are used. The main aim of the directional analysis is to understand the relation between joint directions and directions of the room walls. This relation should give an idea about the rooms if they were carved by considering the joint directions or not. In this study, EW directional model wall is chosen to represent all the walls, as the room geometries are not similar and rather they are various in shapes. Taking the relationship between the joints and the walls into account, the directions of the walls and joints alone do not produce meaningful results. This relationship can only be clarified by the angles between them. Therefore, the directions of the walls are neglected and all the walls are reduced to single direction in order to be able to illustrate the results on the rose diagrams. Since every joint cuts at least two walls of the room, two acute angles between two walls and the joint are used. (Figure 5.1). For the joints juxtapose the walls, 0^{o} value is used twice.

The floor concept is another major problematic issue in that the trend or relation between the walls and the joints would change according to the floors or depth. Firstly, the rose diagrams are applied for each floor to see the modification of the joint directions in 3 dimensions. Then the floors are grouped two by two in order to balance the number of the rooms of the floors. For example, there are twelve rooms at the fourth floor; on the other hand, sixth floor has only three rooms in Derinkuyu. So, floors are grouped as 1-2, 3-4, 5-6 and 7-8 in Derinkuyu and 1-2 and 3-4 in Kaymaklı. Grouping the floors provides a balance in the number of the rooms that are included into analysis together. However, the factors such as the room areas and joint densities of the rooms are not considered during this process. Importance of grouping the floors is that, the floor concept can be linked to historical development of underground city.

As the lengths of the walls and the joints used in rose diagrams are quite different from each other, the equal effect of the each single length on the statistical calculations would yield unreliable results. For this reason, the analyses are performed as weighted and non-weighted. In the weighted analysis, 50 cm unit length is used as a weighted factor (unit length). Each joint or wall is included into the analysis in the number obtained from the ratio of its length to the unit length. Namely, a 100 cm joint or wall is counted twice and its direction value is used twice in the analysis as well.

After directional analysis following rose diagrams are obtained:

- two diagrams for all walls,
- two diagrams for all joints,
- eight and four diagrams for the joints according to the per floor, for Derinkuyu and Kaymaklı, respectively,
- four and two diagrams for the joints according to the grouped floors, for Derinkuyu and Kaymaklı, respectively,
- one diagram for all the acute angles between the joints and walls,
- one diagram for joints in the field.

The interpretations of the analysis are carried out in Chapter 6.

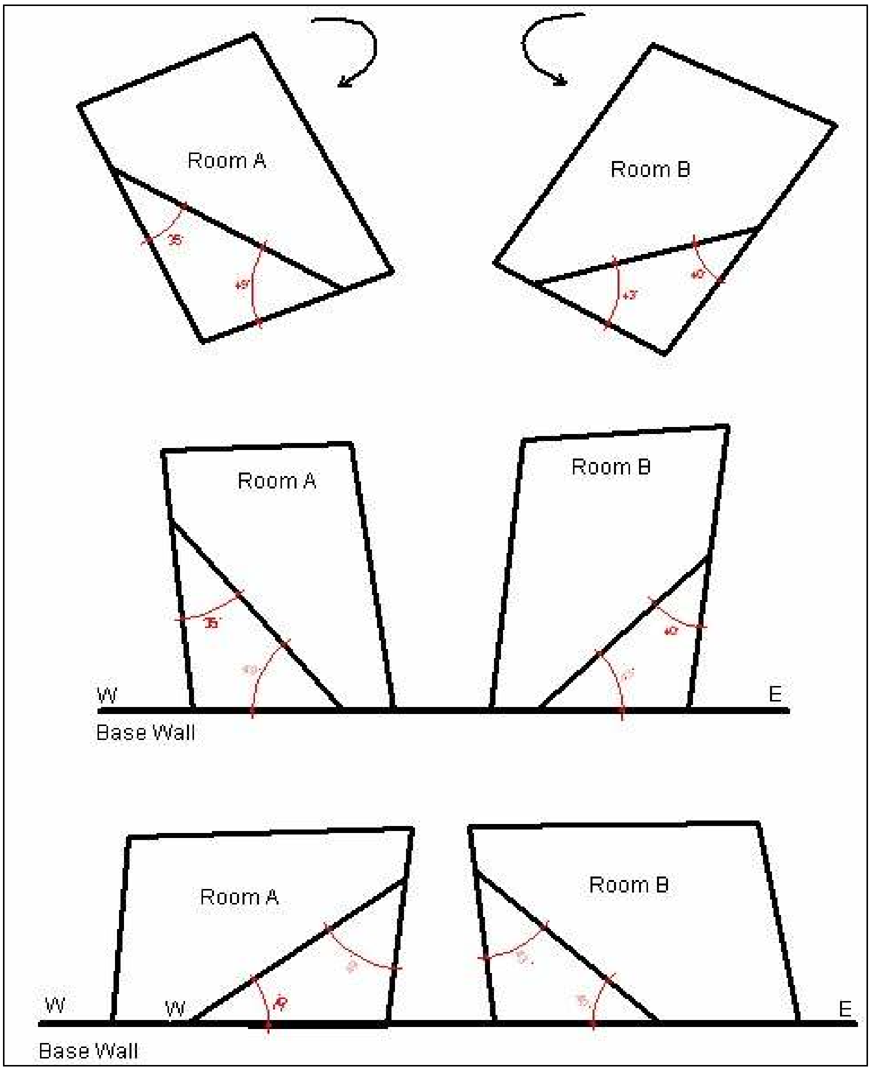


Figure 5.1. The model E-W direction model wall used for the analyses

5.1.1. Directional Analysis of Derinkuyu Underground City

Directional Analysis of the Walls: Two rose diagrams are prepared to represent the direction of walls of Derinkuyu underground city. One of them is non-weighted and one of them is weighted. The weighted factor is chosen 50 cm. Non-weighted rose diagram is prepared from 214 wall directions of 46 rooms (Figure 5.2). There is almost no major trend of wall direction. Without thinking the relation between the joints, these results seem meaningful in that the settlement is under the ground. Accordingly, the criteria like making use of the sunlight, the location of the rooms according to the North direction because of the climatic conditions, or physical and geographical conditions of the settlement area preferred to be able to hide from the enemies do not seem to have any importance in carving of the rooms.

The walls have three dominant directions: N65E-S65W, N5E-S5W and N35W-S35E. Densities of these directions are 11%, 9% and 8% respectively.

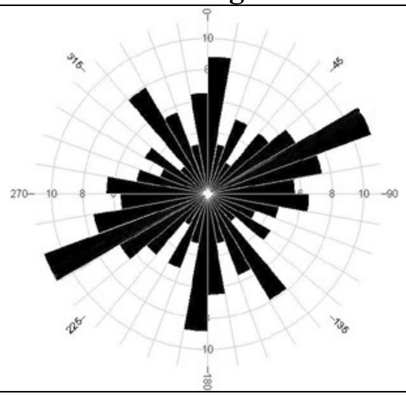
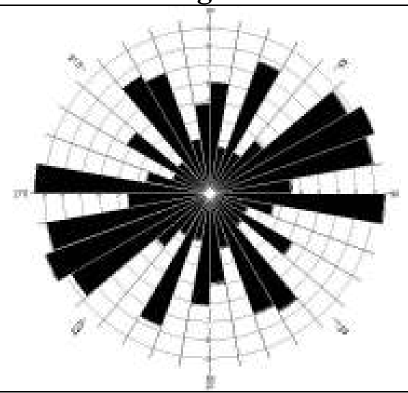
<table>
<tr><th>Non-Weighted</th><th>Weighted</th></tr>
<tr><td>
</td><td></td></tr>
<tr><td>Number of Rooms: 46
Number of Walls: 214</td><td>Number of Rooms: 46
Number of Walls: 1182</td></tr>
</table>

Figure 5.2. Non-weighted and weighted rose diagrams obtained from the walls of Derinkuyu underground city.

Weighted rose diagram is prepared from 1182 wall directions of 46 rooms (Figure 5.2). There is almost no sensible difference between the non-weighted and weighted rose diagrams. The walls are directed in all directions.

Directional Analysis of the Joints: Two Rose diagrams, weighted and non-weighted, are prepared for all joints measured in Derinkuyu. Non-weighted rose diagram (Figure 5.3) shows that:

- There is no major trend for joint directions.
- The measured joints can be represented as a group ranging between NS and N50E directions. In this range the frequency is about 8-12%.

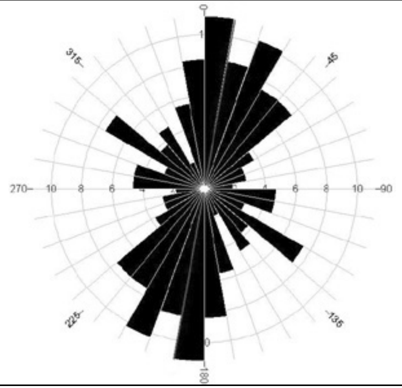
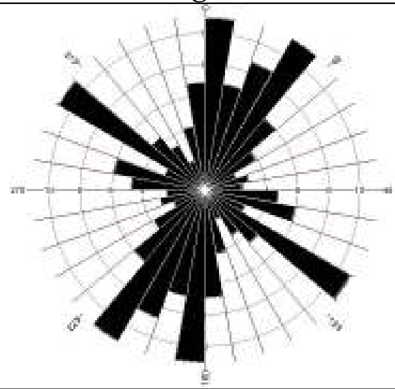
Non-Weighted	Weighted
	
Number of Joints: 104	**Number of Joints= 655**

Figure 5.3. Non-weighted and weighted rose diagrams obtained from the joints of Derinkuyu underground city.

A weighted-rose diagram is prepared, also (Figure 5.3). The major difference between non-weighted and weighted rose diagram is N60W direction is dominant with more than %10 frequency, in weighted analysis. On the contrary, in non-weighted analysis this direction can be neglected.

Directional Analysis of the Joints According to the Floors: Eight rose diagrams are prepared for the acute angles between each walls and joints of the floors separately (Figure 5.4). In these diagrams E-W direction represents the walls. The results obtained from the rose diagrams are as follows:

- In the floor 1, the dominant direction is N65W-S65E (15º to wall) with a frequency of 25 %.
- In the floor 2, the dominant directions are grouped as EW-N60E (0º and 30º to wall) and N25E-S25W (65º to wall) with frequency of 27% and 22%.
- In the floor 3, the dominant direction is N50E (40º to wall) with a frequency of 27%.
- In the floor 4, the dominant directions are grouped as N60E (30º to wall) and N35E (55º to wall) with frequency between 17% and 16%.
- In the floor 5, there are two groups of directions. The dominant direction for the first group is N70E (20º to wall) with a frequency of 25%, and the the

dominant direction for the second one is N45E (45º to wall) with a frequency of 13%.

- In the floor 6, the dominant directions are N40E (50º to wall) and N70E (20º to wall) with the same frequency 25%.
- In the floor 7, the joint angles cluster between N40-80E (50 and 10º to wall) with a frequency of 14%.
- In the floor 8, the major angle direction is N55E (35º to wall) with a frequency of 50%.

Directional Analysis of the Joints According to the Grouped Floors: Four rose diagrams are plotted for the grouped floors (Figure 5.5). The purpose of making binary groups with floors is to normalize the difference of room numbers as to the floors. After grouping, 26 joints are assessed together for the 1st and 2nd floors, 35 joints for the 3rd and 4th floors, 11 joints for the 5th and 6th floors and, 32 joints for the 7th and 8th floors. The following results are obtained after the analyses:

- In floor 1 and 2, the dominant direction is N80E with a frequency of 20%.
- In floor 3 and 4, the main concentration of angles is between EW (parallel to wall) and N30E (60º to wall). The average direction is N55E (35º to wall). The densities vary between the intervals of 11-21%.
- In floor 5 and 6, there are two major groups of angles with dominant directions of N40E (50º to wall) and N80E (16º to wall). The densities are 16% and 22% respectively.
- In floor 7 and 8, the dominant joint set is between N40-80E (50º and 10º to wall) with an average frequency of 15%.

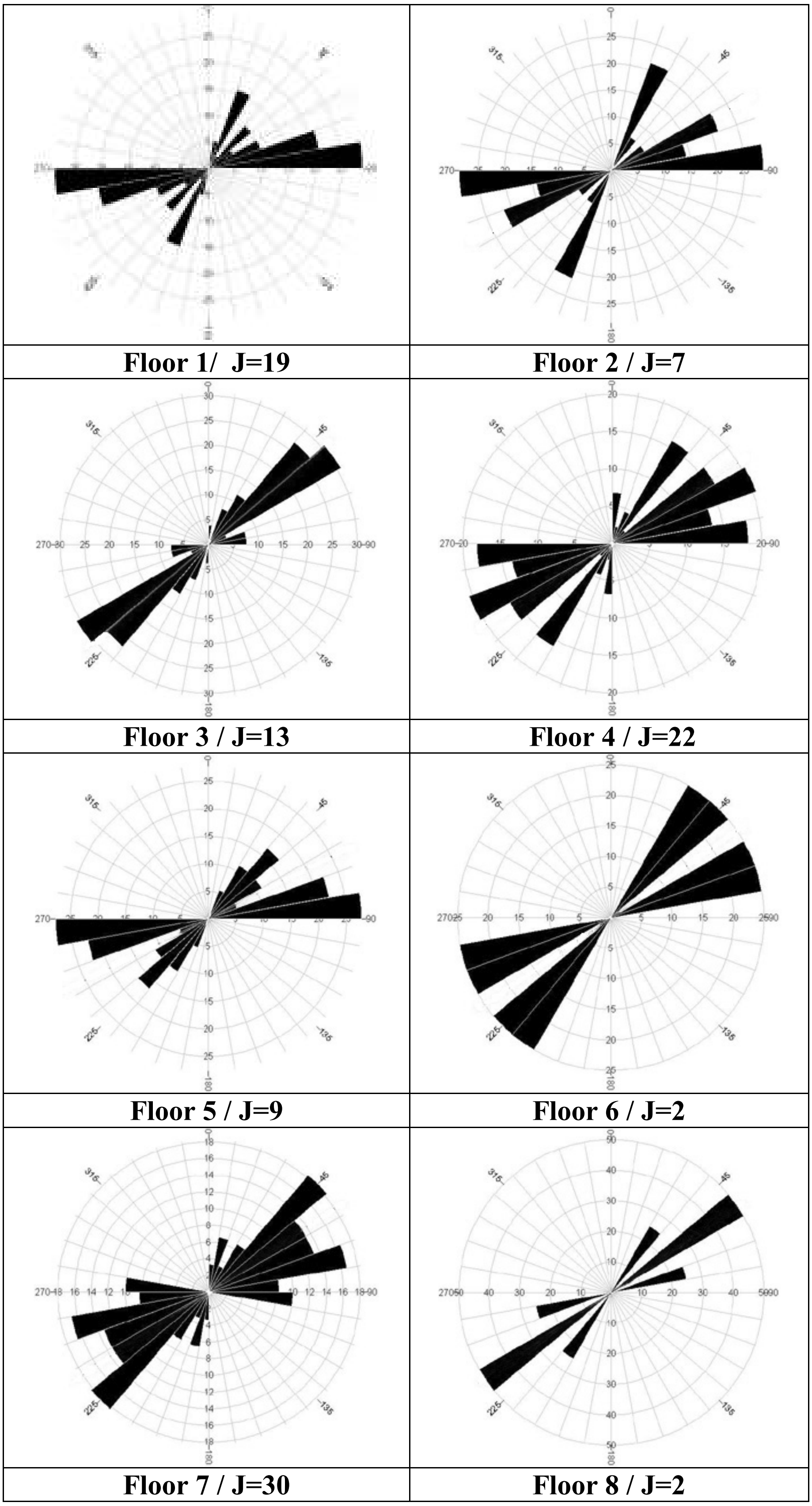


Figure 5.4. Rose diagrams obtained from the measurements of acute angles between the walls and the joints from the floors of Derinkuyu underground city.

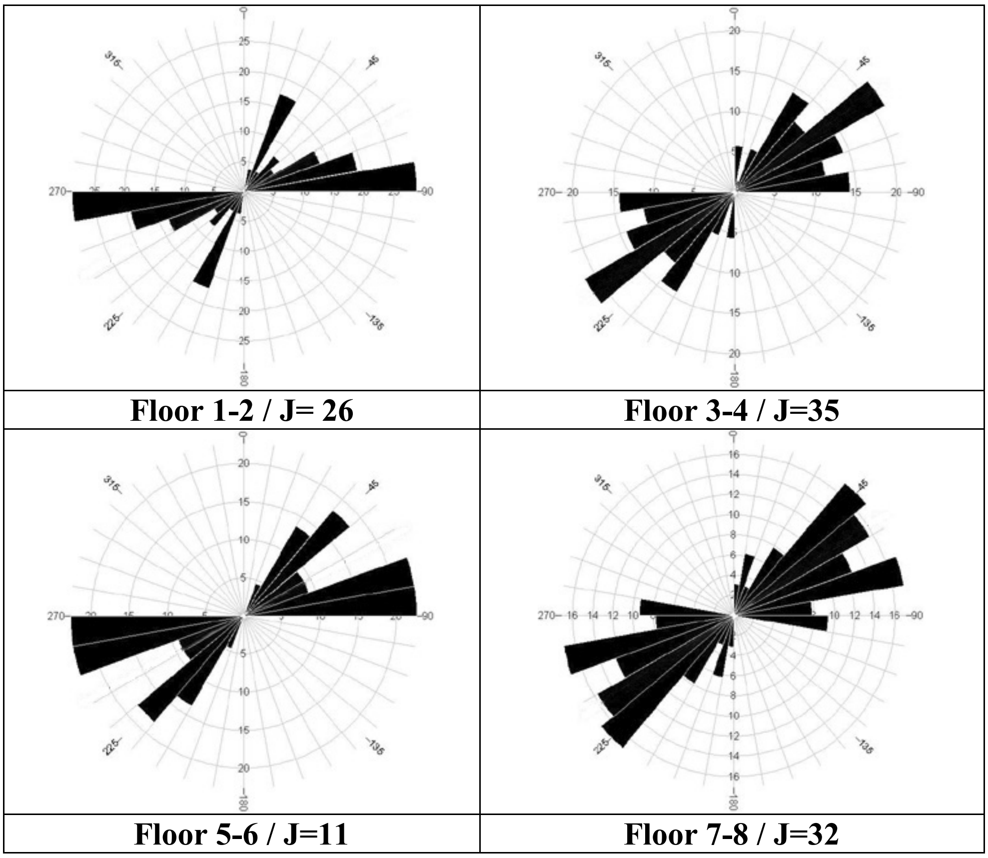


Figure 5.5. Rose diagrams obtained from the grouped floors of Derinkuyu underground city.

Another rose diagram is prepared for the angles between all the joints and the walls (Figure 5.6). In this analysis, it is observed that the main joint set is between EW and N40E (parallel to wall and 50 º to wall).

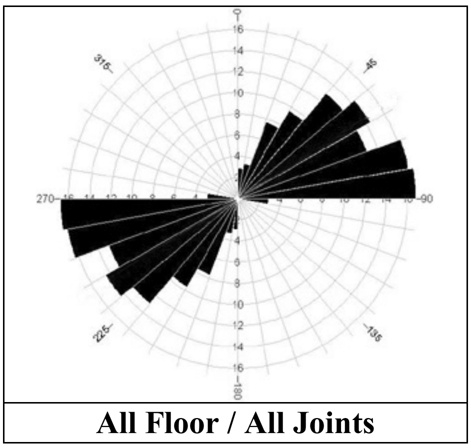
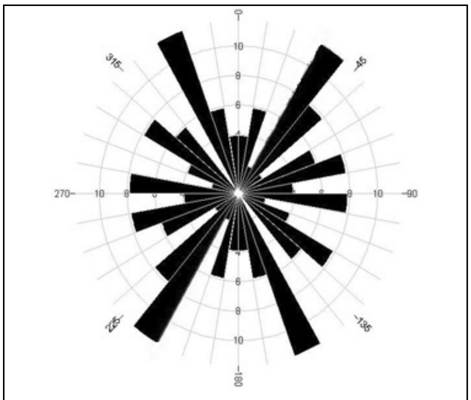


Figure 5.6. Rose diagram obtained from all the angles between the joints and walls of Derinkuyu underground city.

Joints in Field: The field survey is performed from 4 set of joints that measured throughout 4 different lines. The total length of the lines is 80.1 m and total number of joints measured is 50. A rose diagram is prepared by using joint directions (Figure 5.7). The results and comparisons between field and underground city joints are followed:

- There is no exact difference between the joints measured in underground and field according to their direction pattern.
- Since their multi directional structure, there is no definite joint pattern in the field and in the underground city. The joint directions vary in all directions.
- While the joints can be represented as a group ranging between NS-N50E directions with about 8-12% frequency, the dominant directions of joints measured in filed is N35E and N25S directions with the frequency 11%.
- While the EW direction of joints measured in underground city is absent, there is 8% frequency of EW joints in field.



J=50

Figure 5.7. Rose diagram of Kızılkaya joints prepared from field survey in Çekme Köy

5.2. Directional Analysis of Kaymaklı Underground City

Directional Analysis of the Walls: Two rose diagrams, non-weighted and weighted, are prepared for the walls of Kaymaklı in Figure 5.8. Non-weighted analysis is carried out by using 317 walls of 64 rooms in 4 floors. The following results are obtained:

- The wall directions at random in any direction and have random densities.
- The dominant joint direction is N5E with a frequency of 9%.
- By evaluating the results of this analysis together with the directional analysis of the joints, it is hard to say something about the relation between the walls and the joints.

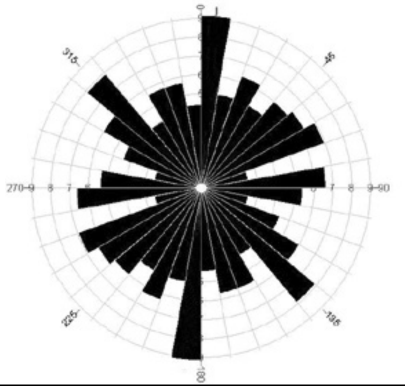
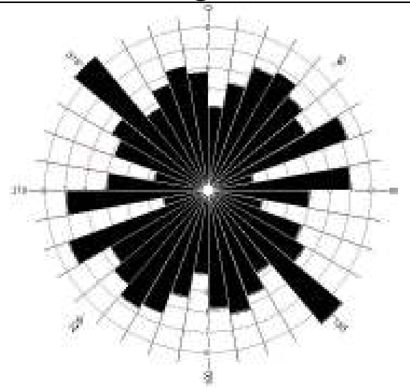
Non-Weighted	**Weighted**
	
Number of Rooms: 64 **Number of Walls: 317**	**Number of Rooms: 64** **Number of Walls: 1545**

Figure 5.8. Non-weighted and weighted rose diagrams obtained from the walls of Kaymaklı underground city.

Weighted analysis is carried out by using 1545 walls of 64 rooms (Figure 5.8). The main difference between two analyses is the dominant joint direction of non-weighted analysis, N5E with 9% frequency, disappears. In the weighted analysis this value decreases to 3.5%.

Directional Analysis of the Joints: Two rose diagrams, non-weighted and weighted, are prepared for all the joint directions measured in Kaymaklı (Figure 5.9). The following results are obtained from the first analysis:

- The major direction is N5E with a frequency of 21%. Furthermore, a group of angles is between the directions of N20-50W with frequency of 13-16%.
- In EW direction, there is a minor direction concentration of 2%.
- The joints are well-organized compared to the joint directions measured in Derinkuyu, and the range of the direction is narrower.

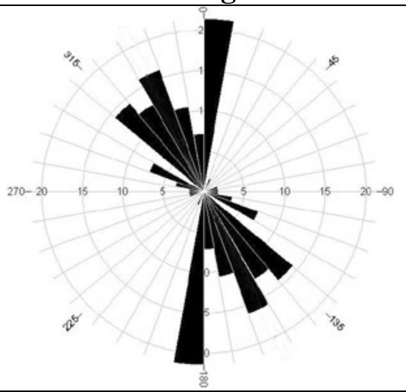
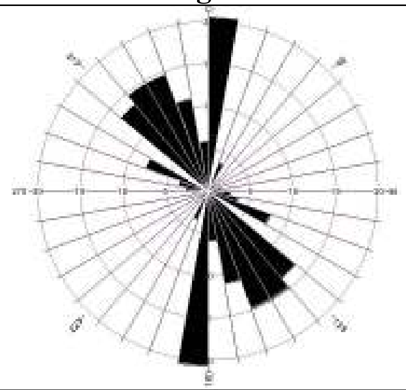
Non-weighted	Weighted
	
Number of Joints: 56	Number of Joints: 306

Figure 5.9. Non-weighted and weighted rose diagrams obtained from the joints of Kaymaklı underground city.

Weighted analysis is carried out to obtained rose diagram of all joints of Kaymaklı (Figure 5.9). There is almost no major difference between the non-weighted and weighted analysis.

Directional Analysis of the Joints According to the Floors: Four rose diagrams are obtained by using the acute angles between the walls and the joints of each floor (Figure 5.10). In these diagrams, E-W direction represents the direction of the walls as it is in Derinkuyu. The results obtained from the rose diagrams could be listed as:

- In floor 1, the dominant direction is N70E (20º to wall) with a frequency of 27 %.
- In floor 2, the angles concentrate in the range of EW-N60E directions with frequency of 17-22%.
- In floor 3, the joints range in a wider interval. The angles can be grouped between EW and N40E directions with frequency of 13-19%.
- In floor 4, the densities of EW directional angles are in minority. The dominant direction is N45E (45º to wall) with a frequency of 32%.

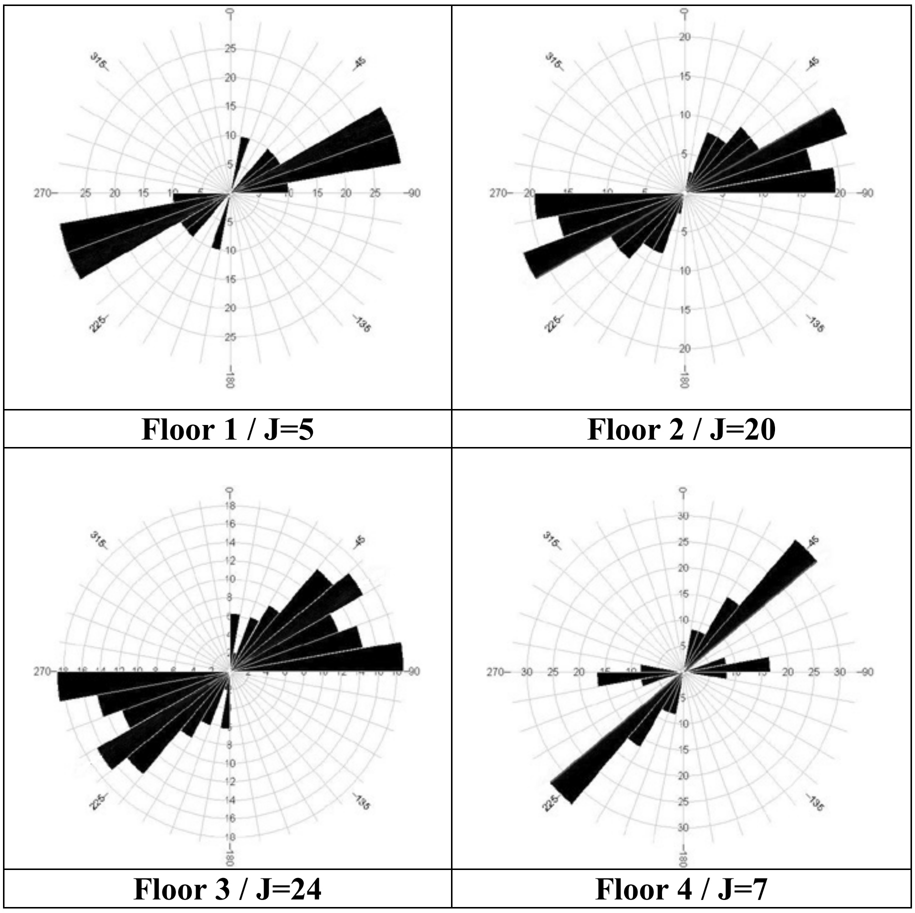
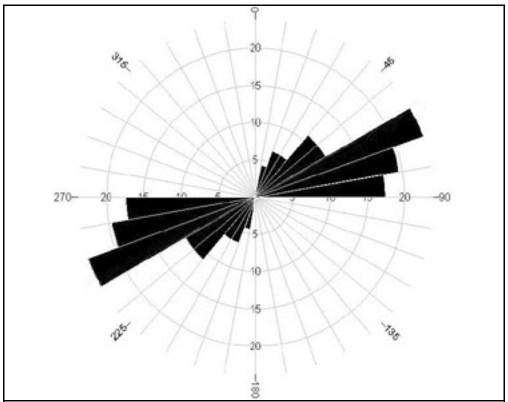


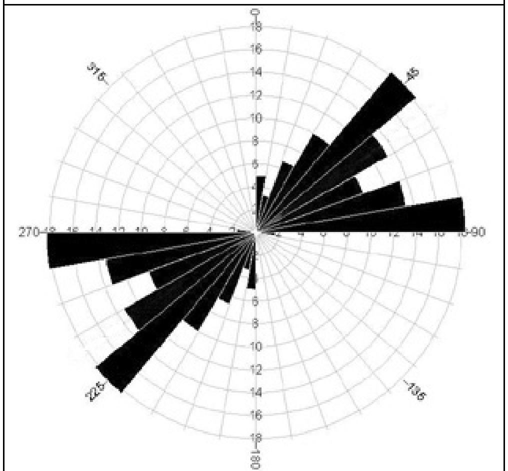
Figure 5.10. Rose diagrams obtained from the measurements of acute angles between the walls and the joints of the floors in Kaymaklı underground city.

Directional Analysis of the Joints According to the Grouped Floors: Two rose diagrams are drawn after grouping the floors (Figure 5.11). The aim of this arrangement is same with that of Derinkuyu. After grouping the floors two by two, 25 joints are assessed in the 1st and 2nd floors together and 31 joints in 3rd and 4th floors. The following results are obtained after the analyses:

- In floor 1 and 2, the dominant direction is N65E (25º to wall) with a frequency of 20%.
- In floor 3 and 4, there are two dominant directions. These are N45E (45º to wall) and N85E (5º to wall) with the same 19% frequency.



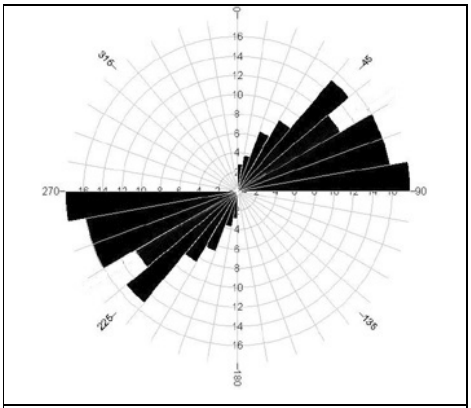
Floor 1-2 / J=25



Floor 3-4 / J=31

Figure 5.11. Rose diagrams obtained from the grouped floors of Kaymaklı underground city.

One more rose diagram is prepared for all acute angles between the walls and the joints in Figure 5.12. In this rose diagram it can be noted easily that in the interval of NW-SE, there is no angle. The mean direction is N58E (32º to wall) and the minimum frequency in this range is 3% for N5E and 18% for N85E.

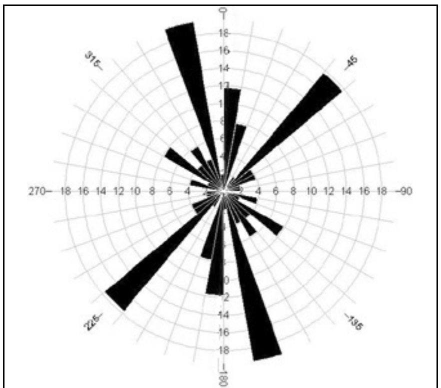


All Floors /All Joints

Figure 5.12. Rose diagram obtained from all the angles between the joints and the walls of Kaymaklı Underground City.

Joints in Field: A rose diagram is prepared for the field survey on Gördeles in Çekme Village (Figure 5.13) from 4 set of joints. The total length of the lines is 120.3 m and total number of joints measured is 51. The results and comparisons between field and underground city joints are followed:

- There are two major joint directions in the field. These are N15W and N45E directions with the frequency of 19% and 18% respectively. The major directions are N5E with a frequency of 21% and a group between the directions of N20-50W with frequency of 13-16%.
- In both measurements there is a minor joint concentration of 2% in EW direction.



J=51

Figure 5.13: Rose diagram of Gördeles joints prepared from field survey in Çekme Village.

5.2. Density Analyses

Density Analyses are carried out to investigate if there is a relation between joint lengths vs. room areas and total number of joints vs. length of room axes. For this purpose, three different density analyses are performed to both processes. Firstly, a density analysis is conducted for the joint densities and for their variations according to the floors in each underground city. The same analyses are also carried out for the grouped floors.

In order to compare the densities of the underground cities, the result of the scatter graphic plotted by using the room areas versus the joint lengths of each underground city is used.

5.2.1. Density Analysis According to Total Joints Lengths and Total Room Areas

In these analyses, the following formula is used to compute the joint densities of the floors:

$$\text{Density of Joints } (m/\ m^2) = \Sigma \text{ Joint Length } (m) \ / \ \Sigma \text{ Room Area } (m^2)$$

Derinkuyu Density Analysis: Joint density analysis is performed for Derinkuyu Site. After computing the densities, the results show that the densities vary between 0.33 m/m² in floor 6 and 0.70 m/m² in floor 3 and floor 5 (Table 5.1).

Table 5.1. Joint densities in the floors of Derinkuyu.

	Σ Joint Length (m)	Σ Room Area (m²)	Density (m/m²)	Number of Joints	Number of Rooms
Floor 1	71.04	141.18	0.5	19	8
Floor 2	25.3	47.98	0.53	7	5
Floor 3	28.9	41.35	0.70	13	6
Floor 4	44.72	64.91	0.69	22	12
Floor 5	29.49	42.13	0.70	9	5
Floor 6	6.46	19.3	0.33	2	3
Floor 7	110.83	176.44	0.63	30	6
Floor 8	4.38	6.38	0.69	2	1

The same density analyses are performed for the grouped floors (Table 5.2). The densities of the floors vary between 0.51 m/m² in floor 1&2 and 0.69 m/m² in floor 3&4.

Table 5.2. Joint densities in the grouped floors of Derinkuyu.

	Σ Joint Length (m)	Σ Room Area (m²)	Density (m/m²)	Number of Joints	Number of Rooms
Floor 1&2	96.34	189.16	0.51	26	13
Floor 3&4	73.62	106.26	0.69	35	18
Floor 5&6	35.95	61.43	0.59	11	8
Floor 7&8	115.21	182.82	0.63	32	7

Two bar graphic tables are obtained from the analyses of single and grouped floors (Figure 5.14 and Figure 5.15). The first graphic implies that there is no major specific trend modification on the joint densities. But the graphic obtained from grouped floors shows that the densities increase towards the deeper floors except for the anomaly between floor 1&2 and 3&4.

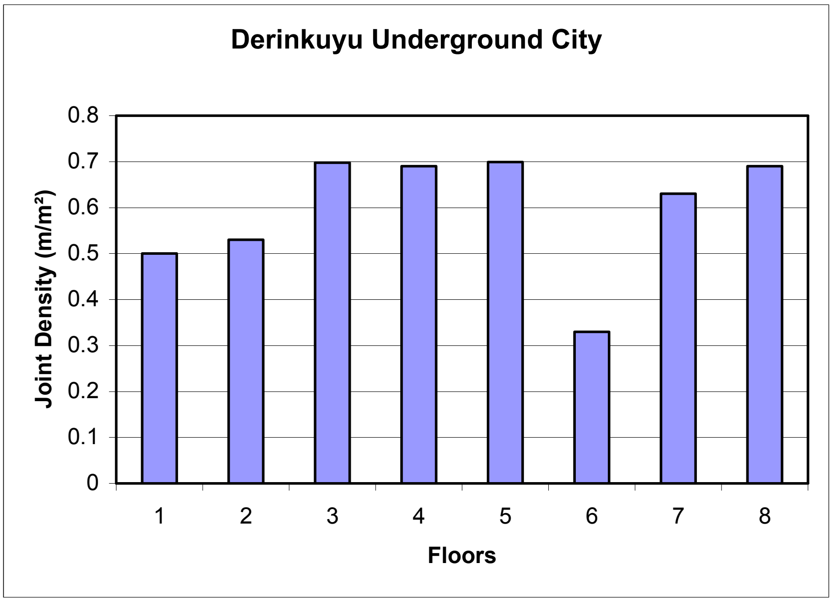


Figure 5.14. Graphic bar projection of joint densities for the floors of Derinkuyu.

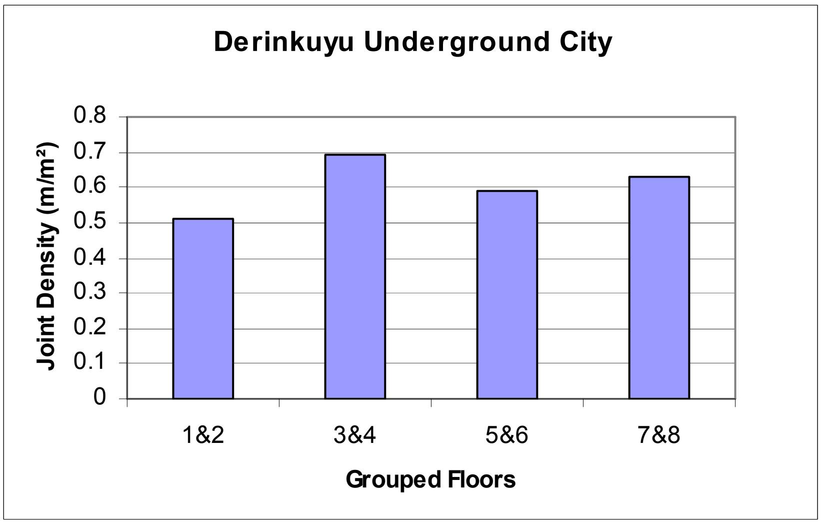


Figure 5.15. Graphic bar projection of joint densities for the grouped floors of Derinkuyu.

Kaymaklı Density Analysis: The same process is followed to see the density changes in Kaymaklı (Table 5.3). The analysis is performed for 4 floors. The densities of the joints vary between 0.13 m/m² in floor 4 and 0.36 m/m² in floor 2.

Table 5.3. Joint densities in the floors of Kaymaklı.

	Σ Joint Lenght (m)	**Σ Room Area (m²)**	**Density (m/m²)**	**Number of Joints**	**Number of Rooms**
Floor 1	20.52	66.58	0.31	5	6
Floor 2	42.87	119.5	0.36	20	14
Floor 3	67.61	293.1	0.23	24	28
Floor 4	19.71	149.3	0.13	7	16

The joint density analyses are performed for the grouped floors once again (Table 5.2). The densities of the floors are 0.2 m/m² in floor 3&4 and 0.35 m/m² in floor 1&2.

Table 5.4. Joint densities in the grouped floors of Kaymaklı.

	Σ Joint Lenght (m)	**Σ Room Area (m²)**	**Density (m/m²)**	**Number of Joints**	**Number of Rooms**
Floor 1&2	63.39	186.08	0.35	25	20
Floor 3&4	87.32	442.4	0.2	31	44

Two bar graphic tables are obtained from the analysis of single and grouped floors (Figure 5.16 and Figure 5.17). Both graphics imply that there is a decreasing trend in the joint densities from top floors to ground floors. The anomaly in the density values between 1st and 2nd floor in the first graphic disappears in the second bar graphic obtained from the grouped floors.

The joint densities of Derinkuyu and Kaymaklı obtained from all the joints and the rooms of the floors are 0.60 m/m² and 0.24 m/m² respectively. So the joint density in Derinkuyu is more than it is in Kaymaklı.

The results can be interpreted as:

- In both of the underground cities, the joint densities vary in different floors. The analyses do not present us an exact argument about the changes of densities according to depth.
- When the floors are grouped, the results of the analyses become more meaningful despite the lack of a precise trend.
- According to the results obtained from the grouped floors, Derinkuyu and Kaymaklı show counter characteristics. While the densities increase towards the deeper floors in Derinkuyu, the densities increase towards the upper floors in Kaymaklı.

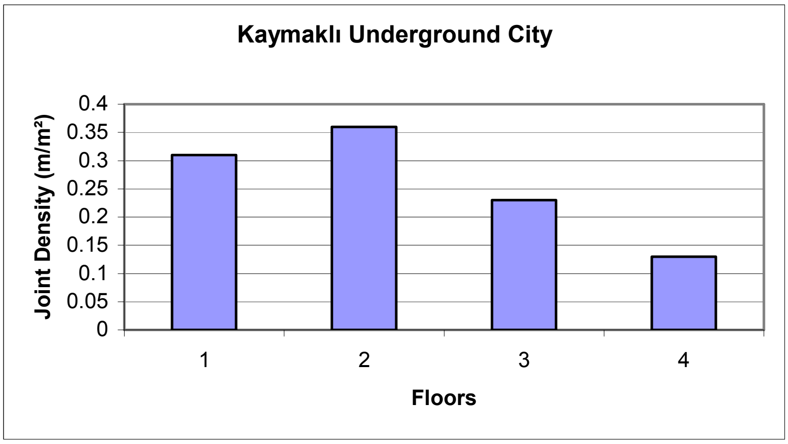


Figure 5.16. Graphic bar projection of joint densities for the floors of Kaymaklı

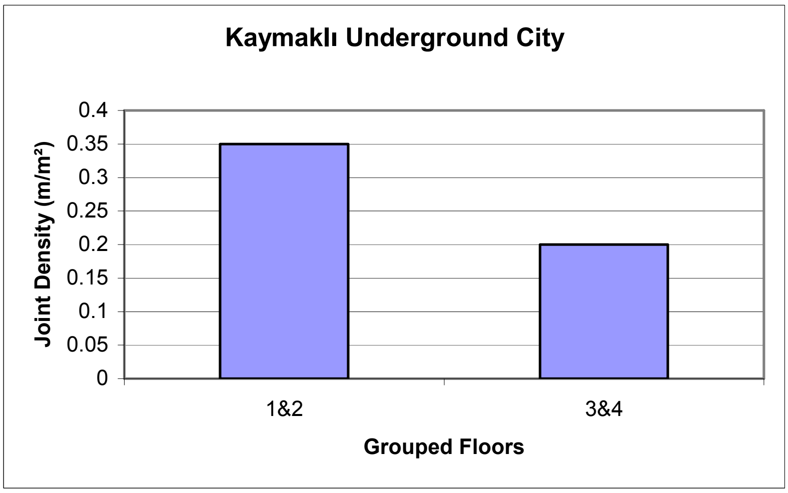
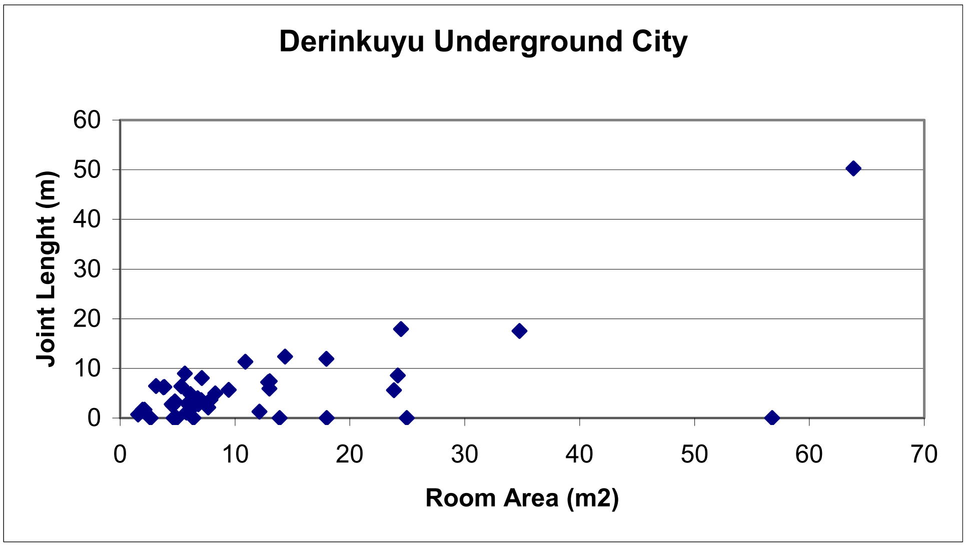


Figure 5.17. Graphic bar projection of joint densities for the grouped floors of Kaymaklı.

5.2.2. Density Analysis According to Room Areas and Joint Lengths

In these analyses, the joint lengths for each room are added and scatter plots for room areas versus joint lengths are obtained (Figure 5.148). The largest room area is 63.83 m² with the total joint length of 50.25 m, while the smallest room area is 1.56 m² with the total joint length of 0.73 m in Derinkuyu. These values are 35.95 m² with 3.71m and 2.40 m² with 1.04m total joint length for Kaymaklı. Although first graph nearly shows a linear form, second graph and its nodes show very scattered form. But it is possible to say that these analyses display that when the room areas increase, joints lengths also increase.



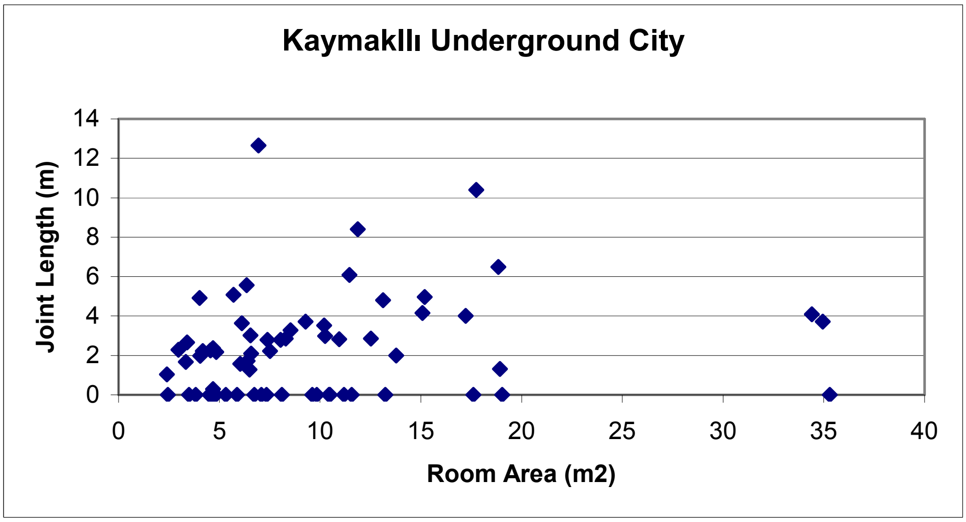
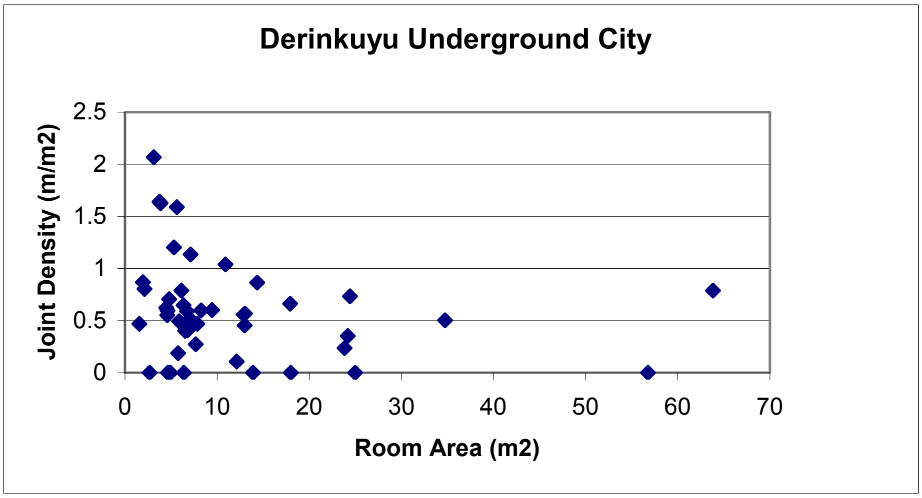


Figure 5.18. Scatter diagrams of room areas vs. joint lengths for both underground cities.

While the analyses are performed by using the area and their joint densities of the rooms, scatter graphics are drawn for two settlements. From the scatter graphics it is not feasible to make an interpretation by using best fit lines, because there is no linear relationship between joint densities and room areas. But it is obvious that the scatter graphics show that the larger rooms have smaller joint densities. This means that while the joint lengths increase in the larger rooms, their densities tend to have decreasing characteristics in both of the underground cities. The following scatter graphs show this relation (Figure 5.19).



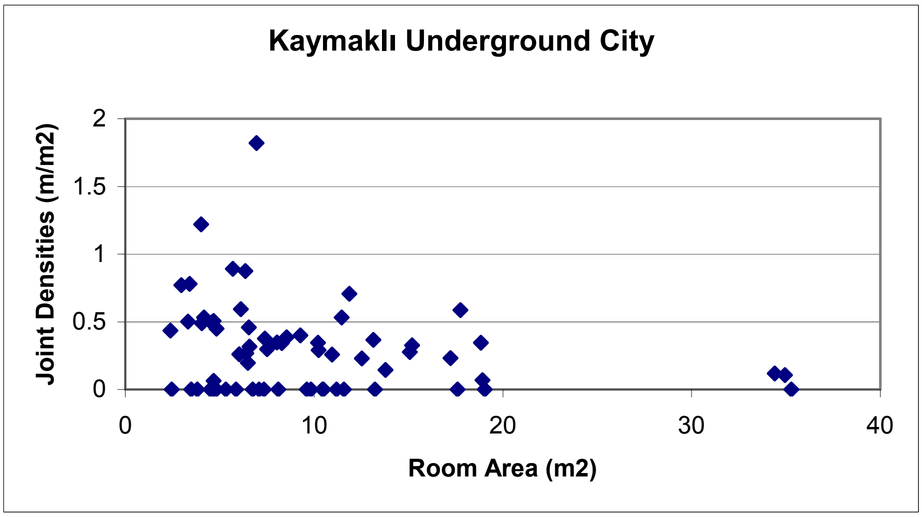


Figure 5.19. Scatter diagrams of room areas vs. joint densities for both the underground cities.

5.2.3. Density Analysis According to Room Axes and Joint Number

In these analyses, the following formula is used to compute the joint densities of the floors:

Density of Joints (#/ m) = Σ Number of Joints / Σ Room Axes (m)

A process similar to field measurements is applied in the rooms of underground cities to compute the joint densities and to compare the underground and field results. In this method axes of the rooms are drawn. While drawing the room axes, the middle points of walls are used and as possible as longest axes are tried to drawn. In the cases like shown in Figure 5.20-A, the axes and joints are extended to crossing and these extra lengths are added to total length of room axes. In the case of absence of intersection between joints and room axis like shown in Figure 5.20-B, more than one axes are drawn to yield the intersection of the room axis with all the joints.

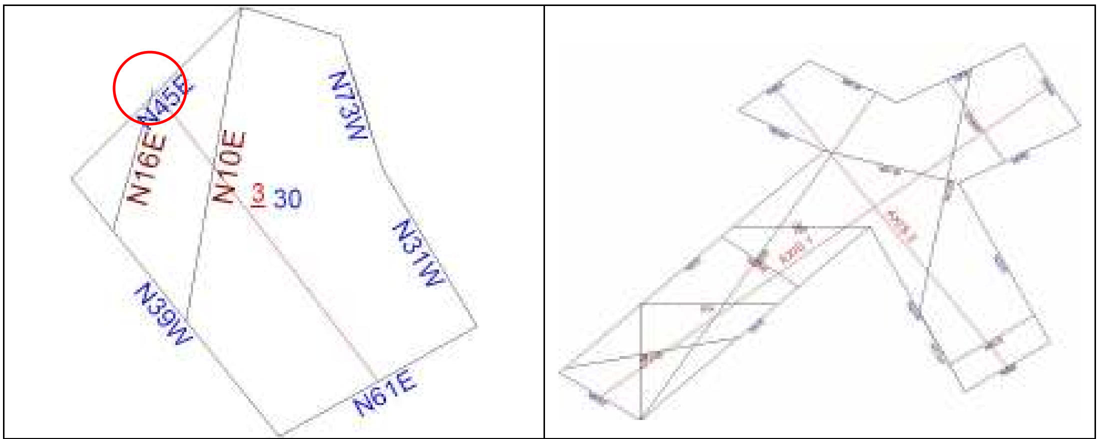


Figure 5.20-A	Figure 5.20-B

Figure 5.20. Method of drawing room axis. A) Extension of joints and room axes, B) Using of two room axes to intersect the all joints.

The density analyses are performed for the rooms and floors (Appendix G and Appendix H). Two bar graphic tables are obtained from the analysis of single and grouped floors for both Derinkuyu and Kaymaklı Underground City. The results of the analyses are the same as the results of density analyses performed according to total number of joints and total areas of rooms.

Derinkuyu Underground City: After performing the density analysis, the results show that the densities vary between 0.36 #/m in floor 6 and 0.66 #/m in floor 8, in Derinkuyu. (Appendix G).

The same density analyses are performed for the grouped floors (Table 5.5). The densities of the floors vary between 0.43 m/m² in floor 1&2 and 0.57 m/m² in floor 3&4. The average joint density of Derinkuyu Underground City is 0.5 #/m. The variations of joint densities between the floors can be followed in Figure 5.21. The variations of joint densities between the grouped floors can be followed in Figure 5.22.

Table 5.5. Joint densities in the floors of Derinkuyu according to number of joints and room axes

Grouped Floor	Σ Length of Axes (m)	Σ Number of Joints	Density (#/m)
1&2	62.48	27	0.43
3&4	59.21	34	0.57
5&6	24.91	12	0.48
7&8	75.2	37	0.49

The first graphic (Figure 5.21) implies that there is no major specific trend modification on the joint densities. But the graphic obtained from grouped floors (Figure 5.22) shows that the densities increase towards the deeper floors except for the anomaly between floor 1&2 and 3&4.

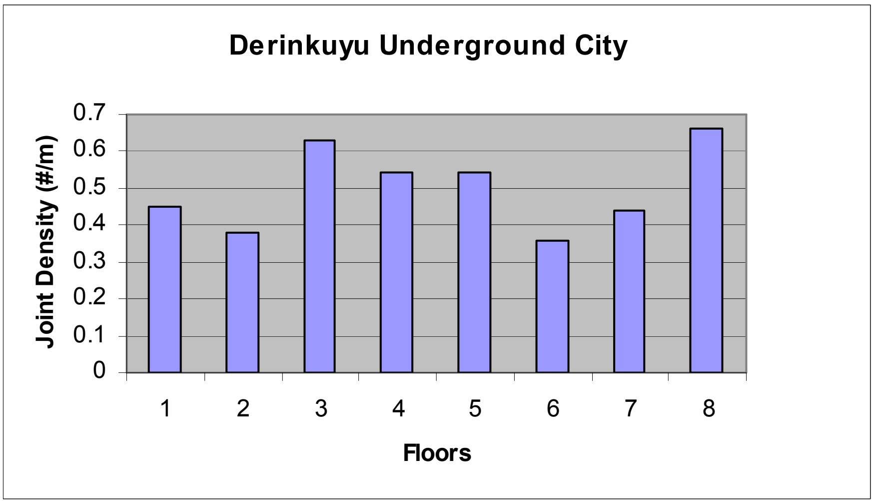


Figure 5.21. Graphic bar projection of joint densities (number of joints/m) for the floors of Derinkuyu (# indicates the number).

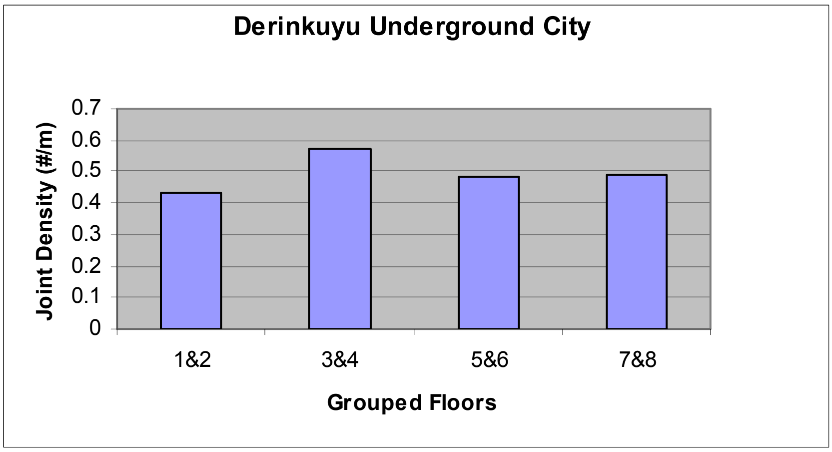


Figure 5.22. Graphic bar projection of joint densities (number of joints/m) for the grouped floors of Derinkuyu (# indicates the number).

Kaymaklı Underground City: The density analysis performed for Kaymaklı shows that the densities vary between 0.11 #/m in floor 4 and 0.44 #/m in floor 2. (Appendix F).

The same density analyses are performed for the grouped floors (Table 5.6). The densities of the floors vary between 0.38 #/m in floor 1&2 and 0.20 #/m in floor 3&4. The average joint density of Kaymaklı Underground City is 0.26 #/m.

The variations of joint densities between the floors can be followed in Figure 5.23. The variations of joint densities between the grouped floors can be followed in Figure 5.24.

Table 5.6. Joint densities in the floors of Kaymaklı according to number of joints and room axes

Grouped Floor	Σ Length of Axes (m)	Σ Number of Joints	Density (#/m)
1&2	65.49	25	0.38
3&4	152.2	31	0.20

Both graphics imply that there is a decreasing trend in the joint densities from top floors to ground floors. The anomaly in the density values between 1st and 2nd floor in the first graphic (Figure 5.23) disappears in the second bar graphic (Figure 5.24) obtained from the grouped floors.

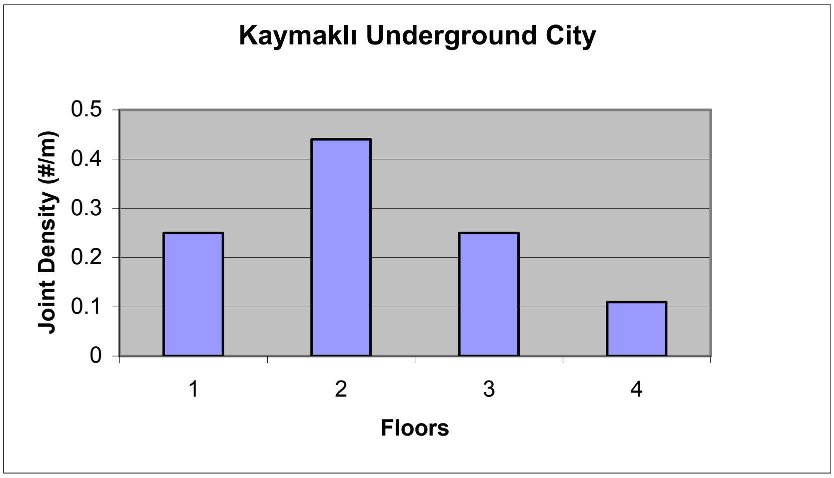


Figure 5.23. Graphic bar projection of joint densities (number of joints/m) for the floors of Kaymaklı (# indicates the number).

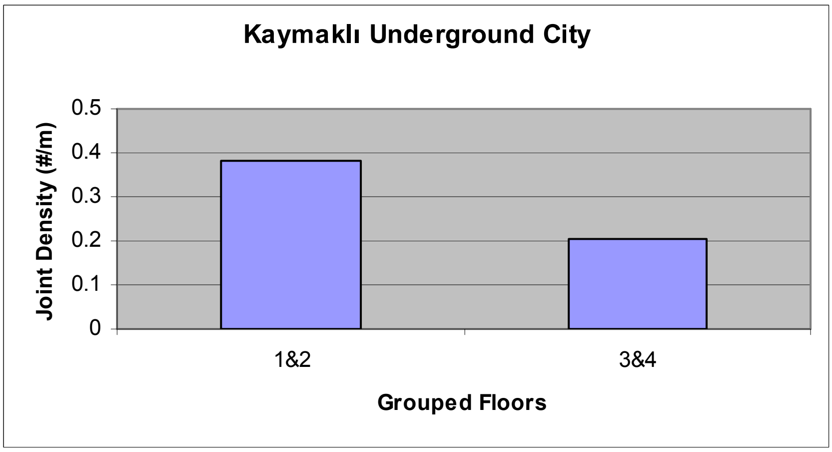


Figure 5.24. Graphic bar projection of joint densities (number of joints/m) for the grouped floors of Kaymaklı (# indicates the number).

5.2.4. Joint Densities in the Field

The density analyses are carried out in the field for Kızılkaya and Gördeles Ignimbrite units. The total length of the 4 survey lines is 80.1 m and total number of joints is 50 in Kızılkaya. The joint density is 0.62 (joint number/m) in this region. When we compare Kızılkaya field joint density with the joint density according to total joint lengths and total room areas in Derinkuyu Underground City (0.6 m/m^2), the values is very close each other. But making a comparison between the results of joint densities in the field and the results of joint density analysis performed according to total number of joint and total length of room axes is more logical and valid, since the method chosen is the same. The joint density of Derinkuyu Underground City according to second method is 0.5 (joint number/ m), very close to the result of first method applied and smaller than the joint density analysis in the field (0.62 joint number/ m).

On the other hand, the joint density of Gördeles in the field, 0.42 joint number/m, is greater than the joint density of Kaymaklı Underground city according to first and second method, 0.24 m/m² and 0.25 joint number/ m. The field survey is carried out from the 4 survey lines that have total length of 120.3 m and 51 joint measurements. The joint density of Kaymaklı Underground City according to second method is 0.25 (joint number/ m), nearly same with the results of first method applied, and smaller than the result of joint density analysis in the field (0.42 joint number/ m).

The joint density of Kızılkaya ignimbrite is higher than Gördeles ignimbrite in both field and underground measurements according to both methods applied.

5.3. Visual Interpretations

In both of the cities, there are rooms having some characteristics due to the joints and their relations with the doors and the pillars. Adequate and necessary interpretation cannot be made only with the statistical analysis and literal interpretation is necessary for more accurate interpretation.

Joints parallel to the walls: The joints are parallel to the walls in rooms 2, 6, 26 in Derinkuyu, and rooms 27, 57 in Kaymaklı (see the figures 4.2, 4.4, 4.9, 4.11) The joint, which is parallel to the wall next to room entrance, in the 26th room of Derinkuyu requires special attention. From the location of the joint it can be deduced that while carving the room, the entrance is intentionally carved there to make use of the joint. In order to carve the walls easily, it might have been preferred to follow the joints along the site (Figure 5.25). In the 6th room in Derinkuyu, and in the 27th, 57th rooms in Kaymaklı, the joints are parallel to side walls. This may mean that during the excavations if a joint was noticed and if the room was seen to have enough size to live in it, carving the room along that direction was ended and the excavation was kept on parallel to the joint to make carving easier.

Figure 5.25. Joint parallel to side wall in Derinkuyu

The same logic is valid for the joints cutting across the entrances vertically or obliquely. As it is easy to carve along such joints, the rooms might have been carved along their directions. The joints in the rooms 1, 2, 3, 4, 6, 11, 13, 14, 15, 21, 22, 23, 24, 25, 31, 32, 38, 40 and 47 in Derinkuyu, and in the rooms 16, 20 28, 31, 37, 45, 50, 60 in Kaymaklı set good examples to the case mentioned above.

Relations between joints and Pillars: There are pillars in the rooms 4, 9 in Derinkuyu and in the rooms 37, 59 in Kaymaklı. Among them, 3 pillars are placed in the centre of the room 4 in Derinkuyu while the other pillars are placed on the room entrances. The joints in the room 4 are on the same direction, and these joins are related with the pillars as one of them juxtaposes one of the pillars and the other is tangential to another pillar (Figure 5.26). The common characteristic of the joints in the exemplary rooms is that none of them cuts across the pillars from the middle. The pillars are formed either as parallel to the joints or as non-intersect the joints. The reason for this might be the assumption that the joints would weaken the pillars or would affect their static. The presence of 7 joints in the room 4 leads us to think that the pillars are built there against the danger of collapse with the logic that the joints would affect the static of such rooms that have larger areas.

Figure 5.26. Joint juxtapose to the pillar in 4th room of Derinkuyu. (J: Joint, P: Pillar)

CHAPTER VI

DISCUSSION

6.1. Lack of Data

Historical Data: There is no information about the carving dates and development process of underground cities. From the literature (SIAL; 1992) it is known that underground cities are carved that in varies rock types. For examples certain rock types are ignimbrite, basalt, basaltic cinder cone, andesite, marble, etc. However, neither the rock type in which the first underground settlement was carved nor their carving sequence is known. It is obvious that there is a time interval between the construction of top and bottom floors since they were carved beginning from the top floor. Yet, it is still unknown whether the people gained experience about the rock types that they deal with while carving.

Geological Data: The most crucial thing is the lack borehole data of the area in geological terms. At present, the information about the buried ignimbrite under the alluvium can be only collected by borehole data. It is especially important to detect the depth of the fluvial material which is also a marker bed between the ignimbrite units. By the help of this data it can be found out whether the city extends till the material that holds the water and the bottom of the host unit or not.

In literature, there is almost no crucial data about the type of ignimbrite in which the underground cities were settled.

Plans of Rooms: The measurements and plans of the rooms of studied underground cities are not available. In order to perform the analysis, the rooms were measured throughout this study. It is necessary to have 2 and 3 dimensional plans of the rooms drawn by the architects or the experts. The absence of this data is a factor that hinders the determination of the levels of rooms and floors.

6.2. Methods Applied

In this study, the cross section across the underground cities are prepared automatically by using a GIS software on the digital elevation model obtained from 1/25000 scale digital maps.

Directional and density analyses are conducted by using the measurements of the walls and joints of the rooms in the underground cities and data of the field measurements. These analyses are applied for each room and grouped rooms in each floors separately. In order to perform the research, the directions and lengths of the walls and joints in each floor are measured. In these analyses it is aimed at finding out some results by considering the relation between the walls and the joints, density relations between the underground cities and between underground and field. These results can be summarized as follows:

- The effects of joints on the location of the rooms,
- The effects of joints on the selection of wall directions while carving the rooms,
- Whether the relationship between the walls and the joints differs according to the floors or not, since this relation is, in the meantime, related to the possibility of people's awareness of existence of the joints throughout the time that the rooms were carved.
- How the joint densities vary according to the floors,
- The variations of the joint lengths according to the room areas,
- How the joints interact with the other parts of the room such as doors, walls, pillars, etc., as to their positions in the room,
- The comparison of the results obtained from two underground cities and field measurements.

The only variable used in analyzing the joint and wall directions/lengths is the floors at which the rooms were carved. However, it should be pointed out that the floor concept used for underground cities is different from its modern usage. Underground cities were carved irregularly and show an unsystematic pattern either in the horizontal space or vertical direction. In both of the underground cities, there is no distinct boundary among the floors, although in Kaymaklı some of the floors lay onto wider and more definite areas compared to Derinkuyu. There are a lot of rooms on the left and right hand of the tunnels which are used to go through from one floor to another. Furthermore, in some parts of the both cities, the difference of the ways while getting down and coming up makes it difficult to understand which level of the down way befit with the same level of the up way. For this reason, the floors that are illustrated in literature guide us through the study. In addition to this, it is observed that the number of the rooms changes from one floor to another (see Appendices A and B). For instance, although there is only one room in the 8^{th} floor and only three rooms in the 6^{th} floor in Derinkuyu, there are twelve rooms in the 4^{th} floor. In order to minimize the confusion in the floor concept and to eliminate the difference in the number of the rooms as to the floors, the floors are grouped two by two. In this way, it is aimed at normalizing the results and decreasing the error margin.

It is also an important criterion for the rooms to have definite geometrical shapes while selecting for measurement. The wide or relatively narrow spaces between or among the rooms are not regarded as separate rooms. Additionally, the rooms that have collapse walls and/or the wall directions of which cannot be identified clearly are not measured. Furthermore, the joints those without clear and continuing appearance on the walls and at the ceiling of the rooms are unregistered. The joints that appear to be man-made (Figure. 6.1) and that have been wiped off their continuity in the course of time because of the collapse or erosion are also not measured.

The measurements are analyzed by using different software. Room drawings of both of the underground cities are prepared by applying GIS software, and different spatial databases are designed for floors, rooms, walls and joints. Their attributes are registered through these databases and many calculations and reports on area, length and density are obtained as automatically from these databases.

As the room geometries do not resemble to, and the directions of the walls are different from each other, the narrow angles between the joints and the walls are measured to make it possible to give a satisfactory explanation on the relationship between the joints and the walls. This application relies on the acceptance of all the walls according to the model wall on the EW direction. The angle values between the walls and the joints are regarded as the angle of the joint to the North according to the EW wall.

First of all, rose diagrams are prepared in accordance with the wall and joint directions by using software. Afterwards, by applying the angle values of the joints as to the model wall, another rose diagram is prepared. The same analyses are performed once again according to the floors grouped two by two (see the Figures 5.5 and 5.11). By these analyses it is aimed at finding out the results such as if there is a definite relationship between the joints and the walls among the floors or not, and how the relations differ according to the depth between these two underground cities.

The density analyses based on the joint length/room area and room axis/number of joints are performed. In these analyses, the floors are repeated by grouping. The graphics of each room area and axes related with the total joint length and numbers of joints are made up on Excel for each room. The joint lengths are illustrated according to the room areas. The results obtained from both of the underground cities are compared and are seen as the characteristics of these underground cities.

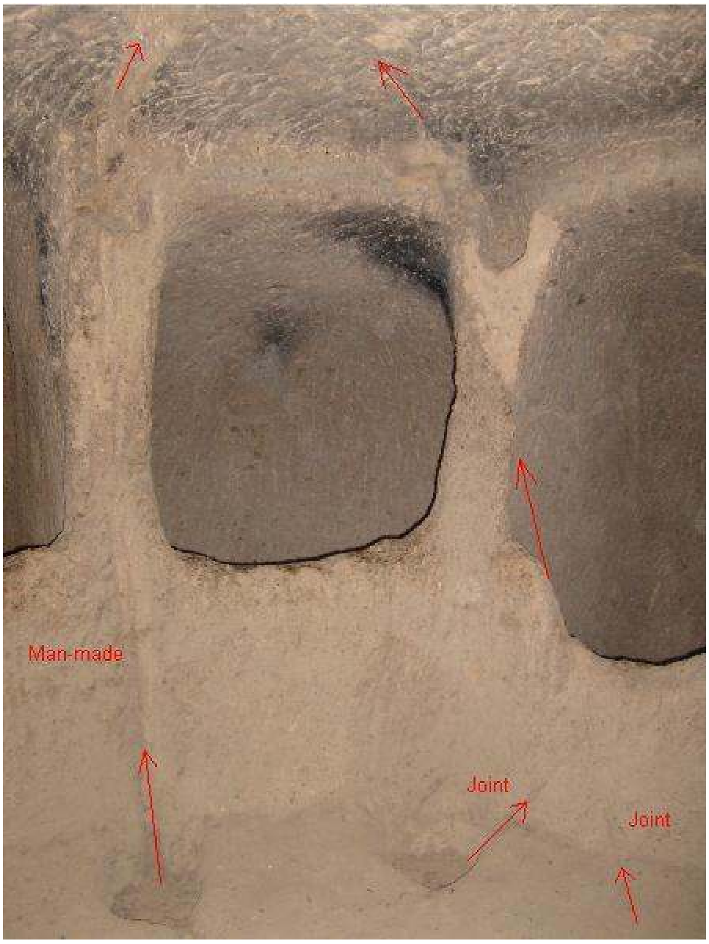


Figure 6.1. Man-made structure and joints in Kaymaklı

No analysis is performed in relation to the volume of the room. Such an analysis would be helpful to have variety in results and to put forward newer arguments. Additionally, no statistical analysis is performed on pillars. The reason for this is that the number of pillars is not enough to carry out such analysis. The relation between the pillars and the joints is illustrated as a visual interpretation (see title 5.4). This interpretation covers the relations of the joints with the corners of the rooms, the walls and the doors.

6.3. Interpretation of Results

Derinkuyu and Kaymaklı underground cities are carved within the Kızılkaya and Gördeles ignimbrites, respectively. Both of the underground cities are located on the downthrown block of the Derinkuyu Fault. The thickness of Kızılkaya and Gördeles ignimbrites observed 13.5 and 34 m, respectively, in the field. The Probable thickness of Derinkuyu and Kaymaklı are 40 and 25 m, respectively. This thickness difference between the underground and field is meaningful and consistent with the morphology of the area. While measured ignimbrites in the field are located on the footwall block and so exposed to the erosion, the underground settlements located on the downthrown block are buried with the continental deposits and preserve their thicknesses.

The non-weighted and weighted directional analysis is performed for the walls, joints of underground cities and joints of field. The results of the analysis are tabulated in Figure 6.2 and Figure 6.3 for Derinkuyu and Kaymaklı, respectively. There is almost no major difference between the weighted and non-weighted analysis results. The directions of the room walls in both of the underground cities scatter to any direction which means that the rooms have no definite directional tendency. Similarly, the directions of the room entrances do not show any consistency. However, the directions of the room entrances and the rooms are not as crucial for the underground settlements as it is for the ground settlements. The reason for this proves itself as the elimination of some factors in the underground cities, such as building and locating the settlements according to the North in order to avoid the wind and cold and making use of the sun light, as well as locating them according to the geographical conditions to provide shelter and convenience (e.g. to build on the slope of a hill).

When thought independently from the walls, although the individual joint directions do not show consistency. Their directions range from NS to N50E in Derinkuyu in non-weighted analysis. The same interval of non-weighted analysis result and N60W direction is observed in weighted analysis. The joint direction varies from N5E to N20W and N50W in Kaymaklı in both non-weighted and weighted analysis. If the horizontal formation of Ignimbrite and the vertical formations of cooling joints against the flow direction are considered, the presence of little joint density between N50E and EW in Derinkuyu, and almost no joint presence between N10E and N70E in Kaymaklı prove themselves as contrary to the generally accepted law. Even though this allows to a supposition that the people took the directions of the joints into account while carving the rooms, still it does not pose a clear answer to their reason of why they avoided the joints on the directions mentioned above. The answer to this question would be made clear in the analyses of the relationship between the walls and the joints.

In analyzing the wall-joint relations, the angle values between the joints and the EW directional model wall are calculated both on a floor scale and on the grouped floors scale as well, since the floors are telescopic to each other and have no clear-cut divisions. In these analyses, while the joint directions in the 1^{st}&2^{nd} floors and 5^{th}&6^{th} floors in Derinkuyu are seen as more parallel to the walls, the joint directions in the other floors are observed as oblique to walls. In the general structure of this underground city, the most evident characteristic derived from the analysis is the presence of little frequency of the joints having perpendicular positions. While there is no perpendicular joint in the 1^{st}&2^{nd} and 5^{th}&6^{th} floors, the frequency of such joints in the 3^{rd}&4^{th} and 7^{th}&8^{th} floors are %6 and %3 respectively. In the whole underground city, this ratio reaches to only 3% which shows us that the people did not prefer to form the room walls that were perpendicular to joints. Similar situation is valid for Kaymaklı also. In Kaymaklı, there is no joint on the NS direction, namely perpendicular to wall, in the 1^{st}&2^{nd} floors and this ratio is 5% in the 3^{rd}&4^{th} floors. The ratio in the whole underground city is 3%. In Kaymaklı the ratio of the joints that are oblique to the walls is more than the perpendicular or parallel joints. It can be said for these two underground cities that the people avoided only the joints perpendicular to the walls.

Density analyses are performed to determine the relation between total room areas and total joint lengths; changing of the joint lengths according to the room areas; relation between the room axis and joint number and, so, in which way the joint densities change according to the floors scale. The minimum density in Derinkuyu is on the 6^{th} floor with a density of 0.36 joint number/m, while the maximum densities are on the 8^{th} floors with a density of 0.66 joint number/m. In Kaymaklı, the minimum density is on the 4^{th} floor with a density of 0.11 joint number/m, and the maximum density is on the 2^{nd} floor with a density of 0.44 joint number/m. In both underground cities, the joint densities show no consistent ascending or descending characteristic. However, after grouping the floors, the analyses have proved to have more regular and meaningful results. The joint densities in Derinkuyu show ascending tendency, while the joint densities in Kaymaklı which have descending tendency from upper floors to lower floors. When the total joint lengths and room areas are illustrated on graphics for both of the underground cities, it is seen that the larger the room area is the longer the lengths of the joints. However, when this analysis is performed according to the room areas and the density of the joints, it is seen that the larger the room area is the lesser the density of the joints. This result may infer to a point that the larger rooms are carved or the room areas are expanded in some parts where the joint densities are lesser.

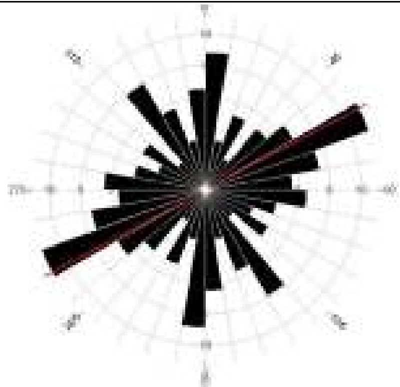
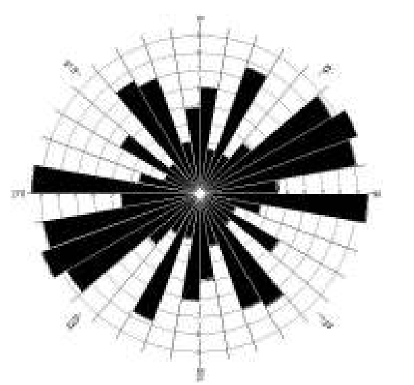
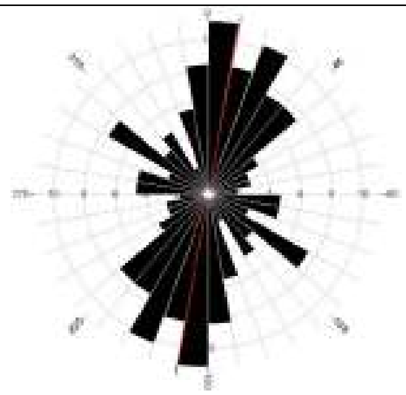
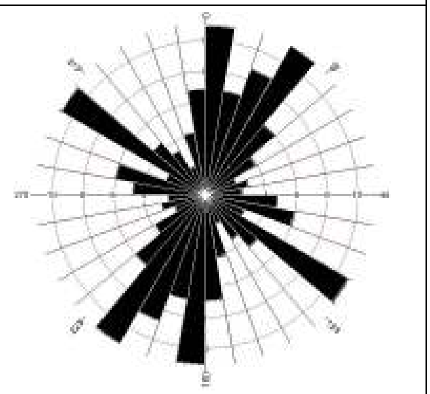
Derinkuyu	Non-weighted	Weighted
Walls		
	Number of Rooms: 46 **Number of Walls: 214**	**Number of Rooms: 46** **Number of Walls: 1182**
Joints		
	Number of Joints: 104	**Number of Joints: 655**

Figure 6.2. Results of weighted and non-weighted directional analysis in Derinkuyu.

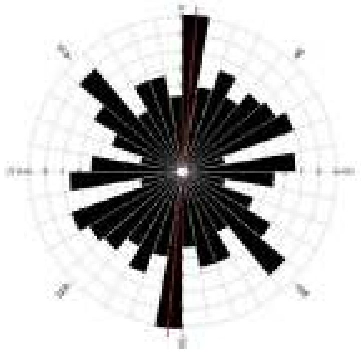
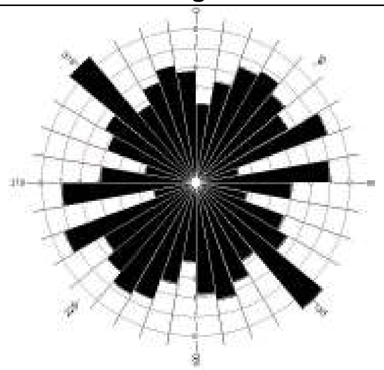
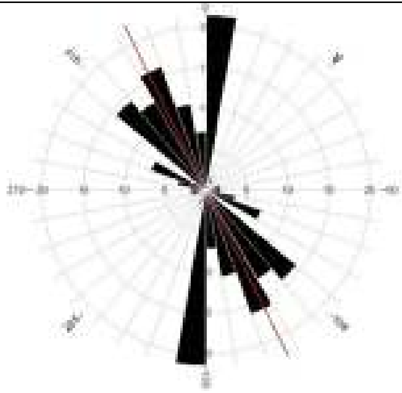
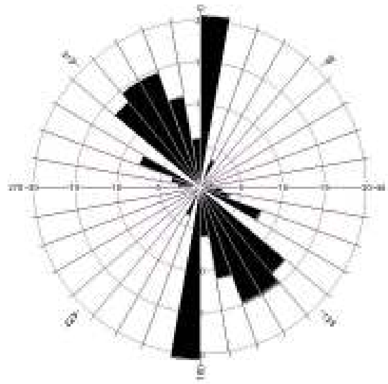
Kaymaklı	Non-weighted	Weighted
Walls		
	Number of Rooms: 64 **Number of Walls: 317**	**Number of Rooms: 64** **Number of Walls: 1545**
Joints		
	Number of Joints: 56	**Number of Joints: 306**

Figure 6.3. Results of weighted and non-weighted directional analysis in Kaymaklı.

The density analyses are also carried out in the field for Kızılkaya and Gördeles Ignimbrite units that Derinkuyu and Kaymaklı Underground cities dug in respectively. The joint density of Kızılkaya is 0.62 (joint number/m) in field survey. This field density value is higher than the joint density in Derinkuyu underground city. Similarly, the result of the field survey in Gördeles Ignimbrite, 0.42 (joint number/m), is higher than the density of Kaymaklı Underground city. These underground and filed density results overlap with the well known information that the upper part of the ignimbrites contains more joints. There is no major joint density difference between the floors in Derinkuyu. But descending trend of joint density towards lower floors is significant in Kaymaklı and the density of the joints measured in filed is greater than those of underground. So the field densities of both Ignimbrite units are consistent with the density trends of underground.

The joint density of Kızılkaya ignimbrite is higher than Gördeles Ignimbrite in both field and underground measurements. It is the natural results of welded structure of Kızılkaya Ignimbrite that is absent for Gördeles. It is already known that the welded ignimbrites are Kızılkaya, Valiababa Tepe and Sarımaden Tepe ignimbrites in the whole Cappadocian region. The relations between Derinkuyu and Kaymaklı underground and filed densities can be followed in Table 6.1.

Table. 6. 1. Joint densities (joint number/m) in underground cities and field.

	Derinkuyu	Kaymaklı
Underground City	0.5	0.26
Field	0.62	0.42

All these results are necessary to have some clues on the major problem which is the question of whether the ancient people took the joints into account while carving these cities or not, and if so, to what extent they thought of it.

The results obtained by these analyses show us that the ancient people were not totally unaware of the presence of the joints while carving and constructing these underground cities. Yet, the measurements, the data obtained and the analyses performed throughout the study are not adequate enough to explain the extent of this awareness. The major physical reason for this deficiency is the scarcity of the data used. For the statistical analyses to bring up more accurate results, it is necessary to increase the number of measurements processed. The areas that can be seen over and examined in Derinkuyu and Kaymaklı Underground Cities are in fact only some parts of the cities. There are many other rooms in both of the cities that have not been dug due to the danger of collapse. Moreover, it is still uncertain that how many floors there are in Kaymaklı Underground City together with the floors that are not illuminated. The scarcity of such data has resulted in the imbalance on the number of the rooms among the floors. For instance, only 3 rooms are analyzed at the 6th floor of Derinkuyu while 12 rooms are analyzed at the 4th floor. In order to eliminate these two problems (imbalanced number of rooms and indistinct boundaries among the floors) and to have more accurate results, the floors are grouped. More general results are drawn from these groupings. If similar analyses were performed after the exposition of the whole underground settlement, it would be easier to have an exact idea on to what extent the joints were taken into account while carving the cities.

Yet, the human beings cannot be thought of as indifferent towards the structures, formations or objects around the environment they choose to live. Although, the data derived from the results is not clear enough to give exact explanations on the relations of the joints with the directions of the walls on the floors scale, the awareness of, avoidance from or making use of the joints can be seen clearly through the visual interpretation on the rooms scale.

CHAPTER VII

CONCLUSION AND RECOMMENDATIONS

7.1. Conclusions

The following conclusions are derived throughout the study about the geology and joint analysis of two underground cities:

1- It is determined that Derinkuyu and Kaymaklı underground cities are carved within Kızılkaya and Gördeles ignimbrites, respectively. The boundaries of these ignimbrites are detected in the close vicinities of settlements, but no boundaries (fluvial deposit markers) are detected within the underground cities.

2- The thickness of Kızılkaya and Gördeles ignimbrites observed 13.5 and 34 m, respectively, in the field. The probable thickness of Derinkuyu and Kaymaklı are 40 and 25 m, respectively.

3- The directions of the room walls in both of the underground cities scatter to any direction which means that the rooms have no definite directional tendency.

4- The most frequent joint directions range from NS to N50E in non-weighted analysis and the same interval of non-weighted analysis result and N60W direction in weighted analysis, in Derinkuyu. The most frequent joint directions vary from N5E to N20W and N50W in Kaymaklı in both non-weighted and weighted directional analysis.

5- By using the results of directional analysis performed to the acute angles between joints and walls, it is detected that in the general structure of Derinkuyu underground city, the most evident characteristic derived from the analysis is the presence of little frequency of the joints having perpendicular positions. In the whole underground city, frequency of NS directed joints reaches to only 3% which shows us that the people did not prefer to form the room walls that were perpendicular to joints. Similar situation is valid for Kaymaklı also. The frequency of NS directed joints in the whole underground city is 3%.

6- The average joint density is 0.5 (joint number/m) in Derinkuyu underground city and 0.26 (joint number/m) in Kaymaklı underground city. The joint densities in Derinkuyu show ascending tendency, while the joint densities in Kaymaklı which have descending tendency from upper floors to lower floors. Joint densities

7- The joint density of Kızılkaya is 0.62 (joint number/m) in field survey which is higher than the joint density in Derinkuyu underground city. Similarly, the joint density of Gördeles in the field is 0.42 (joint number/m) which is higher than the joint density of Kaymaklı underground city.

8- The joint density of Kızılkaya ignimbrite is higher than Gördeles ignimbrite in both field and underground measurements.

9- The information obtained from the results is not clear enough to explain the relations of the joints with the directions of the walls on the floors scale, but the awareness of the joints by the ancient people can be seen clearly through the visual interpretation on the rooms scale.

7.2. Recommendations

The recommendations are presented in this part to contribute to further studies on similar subjects and fields. The following items can provide some clues about the deficiencies of the study and their reasons, the difficulties encountered and suggestions to get over these difficulties.

- The room and floor depths are neglected in this study. The depths of the rooms and floors are taken relatively and the relation among the floors are tried to be determined. However, the confusion on the floor concept has affected the results of the analyses as the level of many rooms remained uncertain according to the floors scale. For further studies, it would give clearer and better results to take depth measurements in each floor and to classify the rooms as to their depth analyses.
- The volume of the rooms is not considered in this study. To perform the density analysis on the volume of the rooms, as it has been performed on the room areas, would set forth crucial results in revealing the room-joint relation.
- The architectural plan applied in the underground cities together with the locations of the rooms according to one another could be important criteria. The presence of collective utilization areas while carving the rooms, and the relations of the rooms to one another in providing comfortable living conditions should be interpreted theoretically by the architects and city planners. If there is undue dispersion throughout the residential area, it should be questioned whether the reason for this would be to avoid the joints while carving.
- Only the lengths and directions of the joints are taken into account throughout this study. If the other criteria on characteristics of the joints such as joint apertures or the continuity of the joints that intersect more than one room are considered, there will be variety in conclusions.
- The presence of pillars is an important factor while carving the rooms. But in this study pillars are not investigated in detail, since there is not enough number of pillars to be measured. But in settlements that have more pillars, the relations between the pillars, the joint densities and the room sizes can be discovered.
- The field survey is applied throughout line sets, because the absence of exposed Ignimbrite surfaces to be measured on top of it in close surroundings. If the field survey should be carried out in an area of surface Ignimbrite, more coherent field joint density results to be used for the comparison with underground joint densities, can be obtained.

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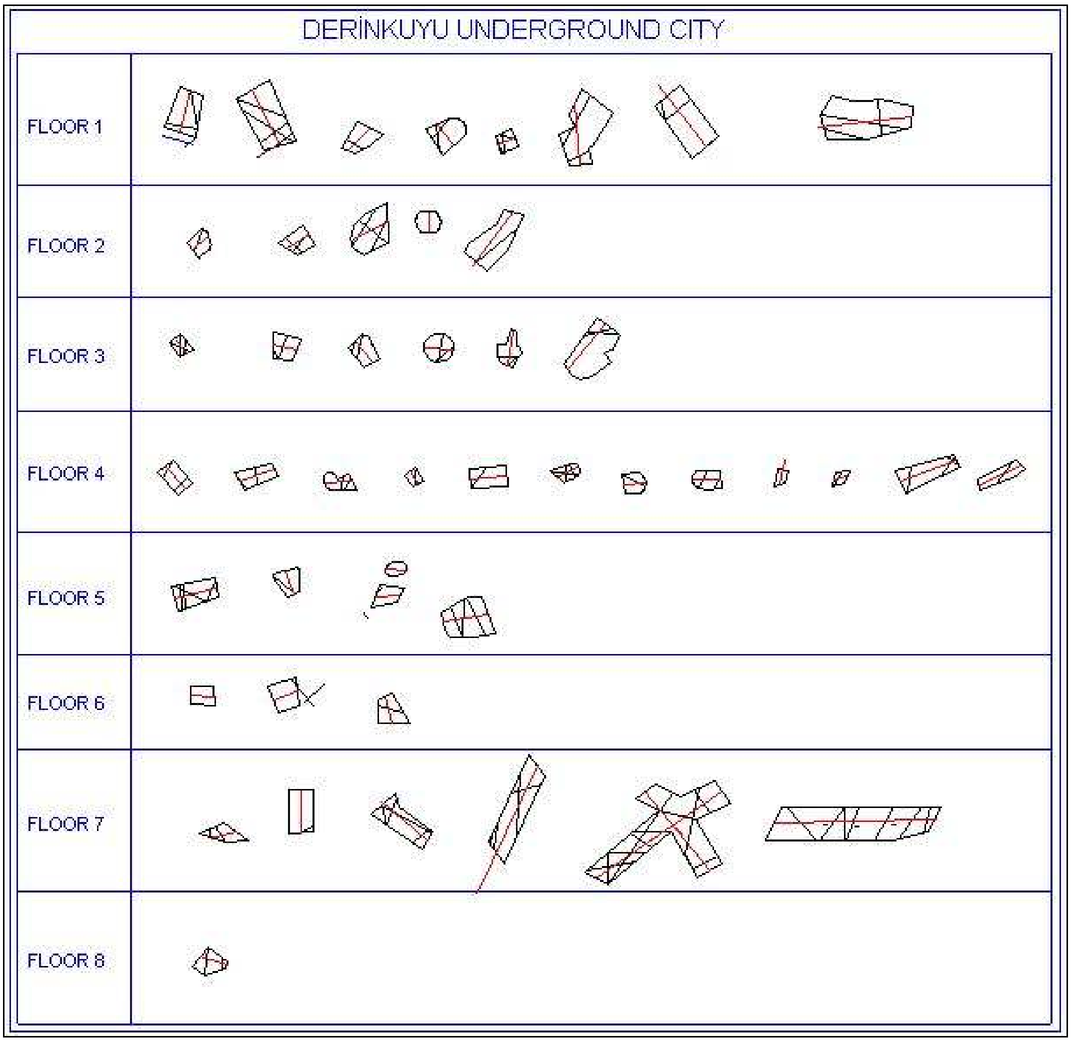
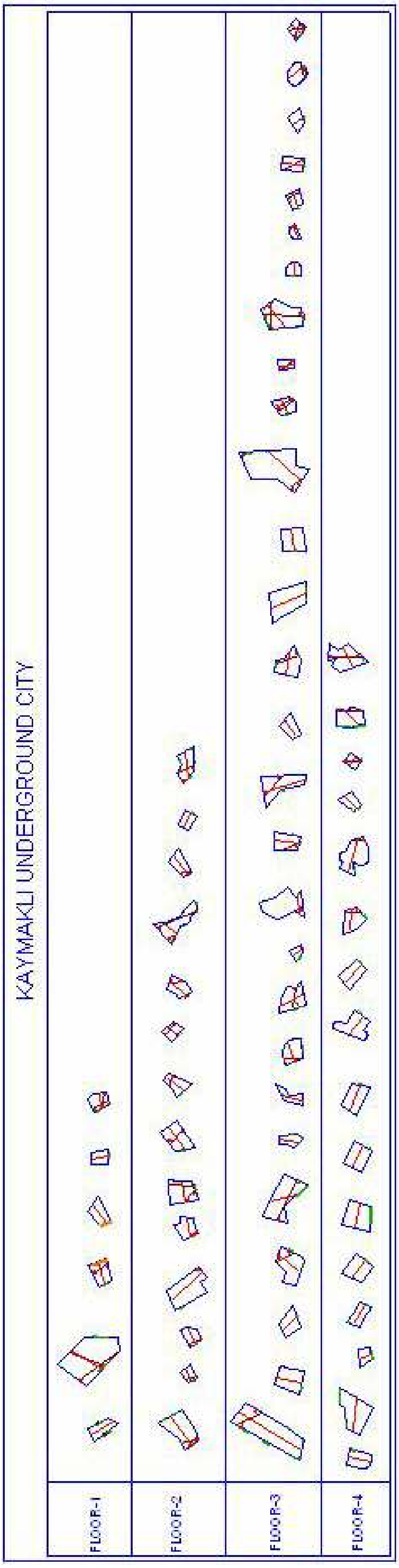
Appendix A

Table A: General View of the Derinkuyu Floors and Rooms



APPENDIX B

Table B: General View of the Floors and Rooms of Kaymaklı



APPENDIX C

Table C: Derinkuyu Underground City Joint and Wall Measurements

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght (m)	Joint Name	Direction
8	**1**	A	N73E	2.38	J-1	N7E
		B	N52W	1.7	J-2	NS
		C	N42E	2.56		
		D	N55W	2.6		
		E	NS	0.79		
7	**2**	A	N55W	6.39	J-4	N33W
		B	N50E	3.35	J-1	N15W
		C	N10W	1.5	J-5	N60W
		D	N55W	4.38	J-2	N10E
		E	N33E	2.17	J-3	N55W
7	**3**	A	N25E	10.22	J-2	N3E
		B	N36W	2.8	J-3	N15E
		C	N25E	10.16	J-4	N10W
		D	N37W	2.77	J-1	N75E
7	**4**	A	N25E	3.85	J-5	N30E
		B	EW	16.65	J-6	N35E
		C	N25E	2.95	J-7	N12E
		D	EW	13.35	J-1	N42W
					J-2	NS
					J-3	N35E
					J-4	N20E
7	**5**	A	N70E	2.8	J-1	N2E
		B	N55W	2.95	J-2	N35W
		C	N84E	2.36		
		D	N16W	2.86		
7	**6**	A	N50E	10	J-1	N80E
		B	N65W	2.74	J-7	N23W
		C	N55E	2.5	J-9	N36E
		D	N65W	2.85	J-8	N57W
		E	N65E	4	J-6	N60E
		F	N35W	2.9	J-2	NS
		G	N65E	3.9	J-4	N35W
		H	N23W	5.3	J-5	N12E
		I	N60E	2.85	J-10	N57W
		J	N23W	5.5	J-11	EW
		K	N50E	8.68	J-3	EW
		L	N60W	2.7		
7	**7**	A	N84E	2.71	J-1	N65E
		B	NS	4.58		
		C	N88E	2.7		
		D	NS	4.4		
6	**8**	A	N35E	3	J-2	N44W
		B	N18E	3		
		C	N80E	2.39		

Table C (Continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght (m)	Joint Name	Direction
		D	N7W	1.4		
6	**9**	A	N30W	3.6	J-1	N58W
		B	N63E	1.7		
		C	N3W	2.34		
		D	EW	3.19		
6	**10**	A	N3W	1.9		
		B	N87W	2.5		
		C	N7W	1.95		
		D	N89W	2.36		
5	**11**	A	N68E	1.45	J-1	N52W
		B	N35W	2.5		
		C	N74E	3.27		
		D	NS	2.25		
5	**12**	A		5.52		
5	**13**	A	N20E	2.46	J-1	N40E
		B	N82W	2.6		
		C	N28E	1.56		
		D	N78E	2.75		
5	**14**	A	N10W	2	J-2	N4E
		B	N61E	2.85	J-1	N25W
		C	N88E	0.6	J-3	N20W
		D	N83E	1.1		
		E	N34W	0.9		
		F	EW	2.5		
		G	N79E	2.38		
		H	N22W	4.18		
5	**15**	A	N15W	2.73	J-2	N6W
		B	N70E	4.4	J-4	N23E
		C	N8W	2.11	J-1	N5W
		D	N78E	4.64	J-3	N63W
4	**16**	A	N25W	2.7	J-1	N8E
		B	N75E	6.3	J-2	N33E
		C	N26W	1.55	J-3	N49W
		D	N66E	4.43		
		E	N61E	1.8		
4	**17**	A	N61E	1.8	J-1	N8E
		B	N66E	2.79		
		C	N40W	1.2		
		D	N53E	1.45		
		E	N79E	3.75		
		F	N25W	1.15		
4	**18**	A	N9W	2	J-1	N62W
		B	N79E	1.75		
		C		2.91		
		D	EW	1.45		
4	**19**	A	N42W	3.2	J-1	N45E

Table C (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght (m)	Joint Name	Direction
		B	N51E	2	J-2	N30E
		C	N42W	3.15		
		D	N50E	2		
4	**20**	A	N76E	3.9	J-1	N5W
		B	N31W	1.6	J-2	N40W
		C	N68E	3.8		
		D	N30W	2.14		
4	**21**	A	N84E	1.55	J-1	N28E
		B	N16E	1.57		
		C	N76E	1.45		
		D	N11W	1.43		
4	**22**	A	N79W	1.06	J-3	N28E
		B	N84E	1.55	J-1	N25E
		C	N11W	1.83	J-2	N87E
		D	EW	2.33		
		E		2.23		
4	**23**	A	N67E	1.1	J-1	N25E
		B	N10E	1.9		
		C	N79W	1.06		
		D	N16E	1.28		
4	**24**	A	EW	3	J-1	N12E
		B	N30W	1.9	J-2	N25E
		C	N65E	1.22		
		D	N40W	0.6		
		E		2.78		
4	**25**	A	N65E	1.22	J-1	N12E
		B	N42W	1.81		
		C	N46E	1.48		
		D	N40W	1.37		
4	**26**	A	N85E	3.85	J-2	N5W
		B	N5W	2.15	J-1	N32E
		C	N85E	3.85		
		D	N5W	2.15		
4	**27**	A	N11W	1.95	J-2	N3E
		B	N67E	0.67	J-3	N85W
		C		2.9	J-1	N18W
		D	N71E	2.3		
3	**28**	A	N46E	1.61	J-1	N70W
		B	N42W	2.2	J-3	N10E
		C	N49E	1.5	J-2	NS
		D	N40W	1.85		
3	**29**	A	N82W	2.15	J-2	N20E
		B	N20E	2.45	J-1	N27W
		C	N75W	3.07		
		D	NS	2.8		
3	**30**	A	N45E	1.9	J-2	N16E

Table C (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght (m)	Joint Name	Direction
		B	N39W	2.6		
		C	N61E	1.78		
		D	N31W	1.43		
		E	N73W	1.09		
3	**31**	A		8.53	J-1	N52E
					J-1	N10E
					J-2	N8E
3	**32**	A	N2E	1.63	J-1	N50E
		B	N65W	0.7	J-2	EW
		C	N19E	1.73	J-1	N50E
		D	EW	0.8		
		E	NS	1.25		
		F	N75W	1.28		
		G	N14E	0.9		
		H	N42E	0.8		
		I	N67W	0.45		
3	**33**	A	N55W	2.25	J-1	N75E
		B	N40E	1.87	J-2	N87W
		C	N36E	4.02		
		D	N55W	0.93		
		E	N75E	1.35		
		F	N55E	2.55		
		G	N66W	1.06		
		H	N55E	0.8		
2	**35**	A		5.27	J-3	N33E
		B	N62E	2.8	J-2	N27E
		C	N2W	4.1	J-1	N50W
		D	N62E	2.8		
2	**36**	A	N38W	2.07	J-1	N22E
		B	N47E	2.16		
		C		4.02		
2	**37**	A		6.51		
2	**38**	A	N75W	1.96		
		B	N23E	4		
		C	N43E	3.12		
		D	N50W	3.25		
		E	N55E	3.45		
		F	N20E	1.75		
2	**39**	A	N55W	2.3	J-2	N50W
		B	N54E	3.1	J-1	N41E
		C	N32W	2.5		
		D	N62E	2.2		
1	**40**	A	N30W	6	J-2	N71W
		B	N75E	3.5	J-1	N58W
		C	N24W	7	J-4	N45E
		D	N59E	4.11	J-3	N45E

Table C (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght (m)	Joint Name	Direction
1	**41**	A	N65W	1.62	J-1	N42W
		B	N61E	1.74		
		C	N49E	1.87		
		D	N64W	3.02		
		E	N22E	3.2		
1	**42**	A	N33W	3.26	J-1	N7W
		B	N47E	3.3	J-2	N42E
		C	N65E	2.7		
		D		2.88		
1	**43**	A	N18W	2.05	J-3	N75W
		B	N65E	1.97	J-1	N5W
		C	N20W	1.94	J-2	N18W
		D	N68E	1.89		
1	**44**	A	N34E	4	J-2	N65E
		B	N52W	4.28	J-1	N29E
		C	N26E	3		
		D	N23W	1.36		
		E	N64E	1.8		
		F	N18W	3.53		
		G	N83E	2.47		
		H	N16W	1.6		
1	**45**	A	N50E	3.75	J-2	N49E
		B	N38W	6.67	J-1	N11W
		C	N50E	3.4		
		D	N35W	6.7		
1	**46**	A	EW	4.24	J-1	N80W
		B	N15W	2.75	J-2	N76W
		C	N35E	2.35		
		D	N75W	2.02		
		E	EW	1.75		
		F	N80E	1.33		
		G	N78W	3.55		
		H	N8E	2.24		
		I	N74E	4.75		
1	**47**	A	N72W	2.4	J-3	N5W
		B	N15E	4.5	J-1	N10W
		C	N8E	4.5	J-2	N80W

APPENDIX D

Table D: Kaymaklı Underground City Joint and Wall Measurements

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
4	**1**	A	N15E	3.25		
		B	N81E	2.42		
		C	N10E	2.15		
		D		2.88		
4	**2**	A	EW	3.62		
		B	N17E	3		
		C	N72W	3.9		
		D	N11E	4.15		
4	**3**	A	N32E	5.73		
		B	EW	2.46		
		C	N38E	0.8		
		D	N85E	2.85		
		E	N24E	2.23		
		F	N62W	4.14		
4	**4**	A	N10W	1.8		
		B	N85E	2.53		
		C	N33W	2.03		
		D	N85E	1.73		
4	**5**	A	N26E	1.74		
		B	N60W	1.7		
		C	N48W	1.75		
		D	N23E	2.2		
		E	N70W	1.4		
		F	N55W	1.89		
4	**6**	A	N36E	3.1		
		B	N55W	3.4		
		C	N27E	3.15		
		D	N55W	2.79		
4	**7**	A	N27E	2.77		
		B	N60W	3.6		
		C	N25E	3.15		
		D	N66W	3.48		
4	**8**	A	N7E	2.62		
		B	N64W	3.4		
		C	N32E	2.5		
		D	N64W	4.51		
4	**9**	A	N55W	2.4		
		B	N20E	1.15		
		C	N20E	0.53		
		D	N20E	4.5		
		E		1.65		
		F		1.6		
		G	N52W	1.43		
		H	N41E	2.64		

Table D (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
4	**10**	A	N43W	3.55		
		B	N48E	2.47		
		C	N49W	3.57		
		D	N48E	2.09		
4	**11**	A	N48E	2.2	J-1	NS
		B	N15W	1.67		
		C	N86W	3.25		
		D	N21W	2.06		
		E	N43W	1.9		
4	**12**	A	N80E	1.85	J-1	NS
		B	N22E	2.3		
		C	N73W	1.04		
		D	N62W	1.77		
		E	N20W	1.88		
		F	N70E	1.8		
		G		4.32		
		H		2.17		
4	**13**	A	N38E	2.6	J-1	NS
		B	N35W	2.3		
		C	N56E	2.43		
		D	N37W	1.49		
4	**14**	A	N45W	1.95	J-1	NS
		B	N31E	1.97		
		C	N46W	1.63		
		D	N40E	1.89		
4	**15**	A	N3E	1.9		
		B	EW	2.57	J-1	NS
		C	N12E	1.5		
		D	N15E	1.6		
		E	N82E	1.9		
		F	N12W	1.67		
		G		0.88		
4	**16**	A	N44E	3.7	J-1	NS
		B	N30W	1.9		
		C	N50E	1.5		
		D	N83W	2.5		
		E	N8W	1.15		
		F	N47W	1.2		
		G	N40E	1.6		
		H	N22W	4.28		
3	**17**	A	N75W	3.06	J-1	N25W
		B	N35E	3.85		
		C	N31E	6.05		
		D	N50W	3.45		
		E	N30E	11.27		
3	**18**	A	N80W	3.4		
		B	N12E	2.75		

Table D (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
		C	N22E	3.85		
		D	N75W	2.15		
		E		1.19		
3	**19**	A	N67E	3.21		
		B	N53W	3.1		
		C	N62E	2.2		
		D	N35W	2.54		
3	**20**	A	N25E	2.75	J-1	N25W
		B	N70W	2.2		
		C	N44E	2.1		
		D	N70W	1.6		
		E	N12E	1.95		
		F	N73W	3.72		
		G	N45E	1		
3	**21**	A	N21E	3.7	J-1	N63W
		B	N60W	2		
		C	N43W	4.7		
		D	N75E	2.5		
		E	N14E	3.7		
		F	N65W	4.7		
3	**22**	A	N40E	1.15		
		B	N5W	2.55		
		C	EW	1.25		
		D	N5E	1		
		E	N12E	1.25		
		F	N44W	1.72		
3	**23**	A	N87E	1.67		
		B	N10W	1.85		
		C	N70E	1.2		
		D	N25E	1.6		
		E	N67E	2.75		
		F	N13E	2.76		
3	**24**	A	N83E	3	J-1	N2E
		B	N16W	2.65		
		C		5.46		
3	**25**	A	N14E	1.3	J-1	N80W
		B	N60W	2		
		C	N85W	2.2		
		D	N19W	4.1		
		E	N75E	3.3		
		F	N58W	1.07		
3	**26**	A	N53W	1.65		
		B	N30W	1.75		
		C	N30W	1.21		
		D	N85E	2.03		

Table D (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
3	**27**	A	N26E	2.5	J-1	N26W
		B	N73E	1.57		
		C	N13W	2.6		
		D	N42W	2.15		
		E	N51E	1.7		
		F	N48W	1.1		
		G	N26W	2.7		
		H	N30E	1.6		
		I	N81E	3.77		
3	**28**	A	EW	2.5	J-1	N20W
		B	NS	3.55		
		C	N81W	1.84		
		D	N10E	3.89		
3	**29**	A	N82W	1.5	J-1	N45W
		B	N3W	6.45		
		C	N80E	4.6		
		D	N50W	3.35		
		E	N14W	3.37		
3	**30**	A	N28W	1.19		
		B	N43E	2.8		
		C	N47W	2.35		
		D	N64E	3.41		
3	**31**	A	N65E	2.45	J-1	N20W
		B	N55E	2.4		
		C	N10W	1.2		
		D	N76W	1.65		
		E	N15E	3.45		
		F	N75W	2.53		
3	**32**	A	EW	3.1		
		B	N16W	5.4		
		C	N85E	4.5		
		D	N36W	1.3		
		E	N29W	4.29		
3	**33**	A	N3W	3.19		
		B	N84E	3.3		
		C	N2W	3.2		
		D	N84E	3.24		
3	**34**	A	N4W	7.99	J-2	N35W
		B	N68E	4	J-1	N70W
		C	NS	3.95		
		D	N40E	2.95		
		E	N55W	3.9		
		F	N16E	2.05		
		G	EW	2.4		
3	**35**	A	N13W	2.28	J-1	N35W
		B	N87W	1.4	J-2	N30W

Table D (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
		C	N14W	2.75		
		D	N37E	1.2		
		E	N56E	2.37		
3	**36**	A	EW	1.15	J-1	N35W
		B	NS	1.35		
		C		1.29		
		D	N80E	1.1		
		E	N5W	2.25		
3	**37**	A	N85E	2.61	J-2	EW
		B	NS	1.3	J-3	N85E
		C	N25E	2.85	J-1	N2E
		D	N36W	2.45		
		E	N64E	3.1		
		F	N5W	4.75		
3	**38**	A	NS	2.25		
		B		4.89		
3	**39**	A	N65E	2.2	J-1	N27W
		B		3.93		
3	**40**	A	N27W	1.65	J-1	N27W
		B	N27W	2.04		
		C	N75E	2.24		
		D	N65E	2.2		
3	**41**	A	N80W	2	J-2	N25W
		B	N6E	3.1	J-1	N32W
		C	N80W	1.95		
		D	N5E	3.1		
3	**42**	A	N50W	1.8	J-1	N38W
		B	N55E	2.5		
		C	N38W	2.25		
		D	N69E	2.21		
3	**43**	A	N50E	1	J-1	N75E
		B		8.35		
3	**44**	A	N50W	2.21	J-1	N7W
		B	N50E	2	J-2	N70W
		C	N50W	1.87		
		D	N40E	1.96		
2	**45**	A	N32W	2.33	J-1	N44W
		B	N75E	1.6	J-2	N5W
		C	N55E	3.57		
		D	N30W	3.75		
		E	N38E	4		
		F	N67E	1.48		
2	**46**	A	N30W	1.55	J-1	N20W
		B	N50E	1.75		
		C	N43W	1.9		
		D	N60E	2.15		

Table D (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
2	**47**	A	N60E	2.5	J-1	N20W
		B	N30W	2.15		
		C	N55E	1.6		
		D		2.44		
2	**48**	A	N32W	5.19	J-1	N5E
		B	N58E	3.3		
		C	N37W	5.55		
		D	N53E	2.05		
		E	N32W	1.03		
		F	N60E	1.69		
2	**49**	A	N20W	2.3	J-1	N48W
		B	N56E	0.85		
		C	N88E	1.42		
		D	N10E	1.85		
		E	N88W	0.82		
		F	N20W	0.9		
		G	N58E	2.44		
2	**50**	A	N68E	2.75	J-1	N48W
		B	N2E	2.6	J-2	N7E
		C	N11W	4.15		
		D	N85E	2.87		
		E		1.41		
2	**51**	A	N10W	2.73	J-1	N45W
		B	N49E	3.4		
		C	N35W	3.07		
		D	N58E	4.54		
2	**52**	A	N65E	1.35	J-1	N48W
		A	N43W	2.88		
		B	N45E	1.7		
		C	N54W	1.25		
		D	N25E	3.47		
2	**53**	A	N32E	1.82	J-1	N48W
		B	N43W	2.27		
		C	N45E	2		
		D	N48W	2.68		
2	**54**	A	N24W	2.19	J-1	N30W
		B	N56E	1	J-2	N5W
		C	N25E	1.2		
		D	N70W	2.08		
		E	N24E	2.13		
		F	N57E	1.82		
2	**55**	A	N55E	0.95	J-3	N35W
		B	N65W	2.9	J-2	N7W
		C	N47E	3.8	J-1	N22W
		D	N14W	2.7		
		E		1.7		

Table D (continued)

FLOOR	ROOM				JOINT	
	Room No	Wall Name	Direction	Lenght	Name	Direction
		F		2.6		
		G	N48W	2.1		
		H		2.132		
2	**56**	A	N42E	3.1	J-1	NS
		B	N52W	2.3		
		C	N60E	3.89		
		D	N30W	1.48		
2	**57**	A	N33E	1.8	J-1	N64W
		B	N65W	2.5		
		C	N24E	1.75		
		D	N64W	2.21		
2	**58**	A	EW	3.72	J-2	NS
		B	N30W	2.95	J-1	N25W
		C	N33E	1.35		
		D	N64W	1.38		
		E	N35E	1.65		
		F	N45W	2.09		
1	**59**	A	N62E	1.67		
		B	N25W	3.2		
		C	N64E	2.3		
		D	N38W	4.27		
1	**60**	A	N46W	6.9	J-2	N20E
		B	N40E	5.1	J-1	N35W
		C	N45W	5.25		
		D	N88E	1.92		
		E	N2E	4.91		
1	**61**	A	N62E	3.33	J-1	N44W
		B	N20W	2.8		
		C	N78E	2.98		
		D	N30W	1.95		
1	**62**	A	N20W	1.84		
		B	N51E	2.65		
		C	N55W	2.46		
		D	N60E	3.97		
1	**63**	A	EW	2.05		
		B	N10W	2.45		
		C	N85E	1.8		
		D	N17W	2.26		
1	**64**	A	N29W	2.39	J-1	N76W
		B	N67E	2.05	J-2	N28W
		C	N55W	0.95		
		D	N10W	2.05		
		E	N80E	1.89		

APPENDIX E

Table E: Joint Density Data in Derinkuyu According to Joint Lengths and Room Areas

Floor	Room No	Room Area (m2)	Joint Lenght (m)	Density
8	1	6.38	0	0
7	2	13.9	0	0
7	3	24.96	0	0
7	4	56.75	0	0
7	5	4.87	0	0
7	6	63.83	50.25	0.78725
7	7	12.13	1.32	0.10882
6	8	7.86	3.69	0.46947
6	9	6.8	2.77	0.40735
6	10	4.64	0	0
5	11	5.85	2.897	0.49521
5	12	2.66	0	0
5	13	4.78	3.37	0.70502
5	14	17.94	11.91	0.66388
5	15	10.89	11.32	1.03949
4	16	12.88	7.2	0.55901
4	17	6.53	2.62	0.40123
4	18	4.64	2.75	0.59267
4	19	6.35	4.1	0.64567
4	20	7.045	3.62	0.51384
4	21	1.96	1.7	0.86735
4	22	5.32	6.4	1.20301
4	23	1.56	0.73	0.46795
4	24	4.49	2.79	0.62138
4	25	2.11	1.7	0.80569
4	26	8.28	4.96	0.59903
4	27	3.75	6.16	1.64267
3	28	3.13	6.47	2.06709
3	29	6.73	3.97	0.5899
3	30	5.78	1.08	0.18685
3	31	7.11	8.06	1.13361
3	32	5.62	8.93	1.58897
3	33	12.98	5.91	0.45532
2	35	14.35	12.4	0.86411
2	36	4.57	2.53	0.55361
2	37	4.95	0	0
2	38	17.99	0	0
2	39	6.11	4.82	0.78887
1	40	24.44	17.94	0.73404
1	41	7.67	2.1	0.27379
1	42	9.44	5.69	0.60275
1	43	3.84	6.24	1.625
1	44	24.16	8.56	0.3543
1	45	23.84	5.63	0.23616
1	46	34.75	17.51	0.50388
1	47	13.03	7.38	0.56639

APPENDIX F

Table F: Joint Density Data in Kaymaklı According to Joint Lengths and Room Areas

Floor	Room Area (m2)	Joint Length (m)	Density
1	7.35	0	0
2	13.23	0	0
3	17.6	0	0
4	3.82	0	0
5	5.87	0	0
6	9.62	0	0
7	10.49	0	0
8	9.84	0	0
9	11.58	0	0
10	8.1	0	0
11	7.51	2.23	0.296937
12	13.78	2	0.145138
13	4.68	0.29	0.061966
14	3.41	2.66	0.780059
15	9.28	3.71	0.399784
16	13.13	4.8	0.365575
17	34.4	4.09	0.118895
18	11.18	0	0
19	7.09	0	0
20	12.53	2.86	0.228252
21	18.84	6.49	0.34448
22	4.65	0	0
23	4.82	0	0
24	8.29	2.85	0.343788
25	10.24	2.99	0.291992
26	2.45	0	0
27	17.23	4	0.232153
28	8.03	2.78	0.346202
29	15.08	4.16	0.275862
30	5.32	0	0
31	10.21	3.52	0.34476
32	19.04	0	0
33	10.45	0	0
34	34.95	3.71	0.106152
35	6.35	5.56	0.875591
36	2.98	2.29	0.768456
37	17.76	10.4	0.585586
38	3.49	0	0
39	2.4	1.04	0.433333
40	4.06	1.98	0.487685
41	6.11	3.63	0.594108
42	4.56	2.25	0.493421
43	6.58	2.09	0.317629

Table F (Continued)

Floor	Room Area (m2)	Joint Length (m)	Density
44	4.03	4.91	1.218362
45	15.19	4.97	0.327189
46	3.33	1.67	0.501502
47	4.84	2.17	0.448347
48	18.93	1.32	0.069731
49	6.5	1.28	0.196923
50	11.46	6.09	0.531414
51	10.95	2.82	0.257534
52	6.04	1.57	0.259934
53	4.68	2.37	0.50641
54	6.55	3.01	0.459542
55	11.87	8.4	0.707666
56	6.41	1.71	0.266771
57	4.18	2.22	0.5311
58	8.54	3.28	0.384075
59	6.95	12.66	1.821583
60	35.29	0	0
61	7.39	2.79	0.377537
62	6.74	0	0
63	4.51	0	0
64	5.7	5.08	0.891228

APPENDIX G

Table G: Density Analysis of Derinkuyu According to Joints Numbers and Room Axes

Floor	Room No	Area(m2)	Axis	Number of Joint	Density
8	1	6.38	3.02	2	0.66
		Σ	**3.02**	**2**	**0.66**
7	2	13.9	6.44	5	0.78
	3	24.96	15	4	0.27
	4	56.75	16.85	7	0.42
	5	4.87	2.89	2	0.69
	6	63.83	15.88	9	0.57
			10.58	4	0.38
	7	12.13	4.55	1	0.22
		Σ	**72.18**	**32**	**0.44**
6	8	7.86	3.01	2	0.66
	9	6.8	2.82	1	0.35
	10	4.64	2.43	0	0
		Σ	**8.26**	**3**	**0.36**
5	11	5.85	2.62	1	0.38
	12	2.66	2.07	0	0
	13	4.78	2.64	1	0.38
	14	17.94	4.80	3	0.62
	15	10.89	4.51	4	0.89
		Σ	**16.64**	**9**	**0.54**
4	16	12.88	6.24	3	0.48
	17	6.53	4.88	1	0.21
	18	4.64	2.37	1	0.42
	19	6.35	3.18	2	0.63
	20	7.04	3.84	2	0.52
	21	1.96	1.49	1	0.67
	22	5.32	3.07	2	0.65
	23	1.56	2.64	1	0.38
	24	4.49	3	2	0.67
	25	2.11	1.59	1	0.63
	26	8.28	3.85	2	0.52
	27	3.75	2.47	3	0.2
		Σ	**38.61**	**21**	**0.54**
3	28	3.13	2.04	3	0.2
	29	6.73	2.78	2	0.72
	30	5.78	2.85	2	0.7
	31	7.11	3.04	2	0.66
	32	5.62	3.72	2	0.54

Table G (continued)

Floor	Room No	Area(m2)	Axis	Number of Joint	Density
3	33	12.98	6.16	2	0.32
		Σ	**20.6**	**13**	**0.63**
2	35	14.35	4.23	3	0.71
	36	4.57	2.26	1	0.44
	37	4.95	2.23	0	0
	38	17.99	7.13	1	0.14
	39	6.11	2.64	2	0.76
		Σ	**18.5**	**7**	**0.38**
1	40	24.44	6.49	4	0.62
	41	7.67	3.33	1	0.3
	42	9.44	2.95	2	0.68
	43	3.84	1.93	3	0.2
	44	24.16	6.62	2	0.3
	45	23.85	8.37	2	0.24
	46	34.75	9.81	3	0.31
	47	13.03	4.47	3	0.67
		Σ	**43.98**	**20**	**0.45**
		Σ	**211.21**	**105**	**0.5**

APPENDIX H

Table H: Density Analysis of Kaymaklı According to Joints Numbers and Room Axes

Floor	Room No	Area (m2)	Axis	Number of Joint	Density
4	1	7.35	3.40	0	0
	2	13.23	3.72	0	0
	3	17.6	4.76	0	0
	4	3.82	1.88	0	0
	5	5.87	3.34	0	0
	6	9.62	3.1	0	0
	7	10.49	3.54	0	0
	8	9.84	3.87	0	0
	9	11.58	3.36	0	0
	10	8.104	3.56	0	0
	11	7.51	3.09	1	0.32
	12	13.78	4.89	1	0.2
	13	4.68	2.49	1	0.4
	14	3.41	1.79	1	0.56
	15	9.28	3.29	1	0.3
	16	13.13	3.18	1	0.3
		Σ	**53.26**	**6**	**0.11**
3	17	34.4	10.58	1	0.1
	18	11.18	3.68	0	0
	19	7.09	2.79	0	0
	20	12.53	4.01	1	0.25
	21	18.84	3.80	1	0.26
	22	4.65	2.85	0	0
	23	4.82	3.14	0	0
	24	8.29	3.05	1	0.33
	25	10.25	3.82	1	0.26
	26	2.45	1.81	0	0
	27	17.23	2.9	1	0.35
	28	8.03	3.71	1	0.27
	29	15.08	6.22	1	0.16
	30	5.32	3.05	0	0
	31	10.21	3.29	1	0.3
	32	19.04	5.45	0	0
	33	10.45	3.27	0	0
	34	34.95	6.46	2	0.31
	35	6.35	2.32	2	0.86
	36	2.98	2.35	1	0.43
	37	17.76	4.29	3	0.7
	38	3.49	1.82	0	0
	39	2.4	2.14	1	0.47
	40	4.06	2.22	1	0.45
	41	6.11	3.1	2	0.65
	42	4.56	1.93	1	0.52
	43	6.58	2.90	1	0.34

Table H (continued)

Floor	Room No	Area (m2)	Axis	Number of Joint	Density
3	44	4.03	1.98	2	1.01
		Σ	**98.93**	**25**	**0.25**

2	45	15.19	5.18	2	0.39
	46	3.33	1.94	1	0.52
	47	4.84	2.49	1	0.4
	48	18.93	6.00	1	0.17
	49	6.5	2.72	1	0.37
	50	11.46	3.01	2	0.67
	51	10.95	3.96	1	0.25
	52	6.04	3.14	1	0.32
	53	4.68	1.90	1	0.53
	54	6.55	2.96	2	0.68
	55	11.87	2.6	3	1,2
	56	6.41	3.48	1	0.29
	57	4.18	2.36	1	0.42
	58	8.54	3.76	2	0.53
		Σ	**45.49**	**20**	**0.44**

1	59	6.95	3.72	0	0
	60	35.29	5.18	2	0.39
	61	7.39	3.13	1	0.32
	62	6.74	3.30	0	0
	63	4.51	2.39	0	0
	64	5.7	2.28	2	0.88
		Σ	**20**	**5**	**0.25**

Σ	**217.68**	**56**	**0.26**

APPENDIX I

Table I: Field Survey Data of Kızılkaya Ignimbrite

Measurement Lines	**Set 1**	**Set 2**	**Set 3**	**Set 4**
Direction of the Lines	N33W	N71E	N72E	N27E
Length of the Lines	L=16.2	L=24.3	L=22.5	L=17.1
Joint Directions	N67E	N61E	N14W	N54W
	N32W	N14E	N72E	N06E
	N28E	N74W	N12W	N88E
	N84W	N12W	N87E	N08W
	N18E	N88E	N34W	N44E
	N77W	N22E	N54E	N32W
	N56E	N24E	N27W	N61W
	N43E	N48W	N83E	N36W
	N84W	N53E	N22E	N37W
	N18E	N42W	N46W	
	N79W	N06W	N34W	
	N33E	N56E		
	N69W	N23E		
		N74W		
		N02E		
		N44W		
		N62W		
		N44E		

APPENDIX J

Table J: Field Survey Data of Gördeles Ignimbrite

Measurement Lines	**Set 1**	**Set 2**	**Set 3**	**Set 4**
Direction of the Lines	N70E	N70E	N77E	N77W
Length of the Lines	39.6	29.7	32.4	18.9
Joint Directions	N74W	N13E	N33E	N44W
	N68W	N69W	N13E	N32E
	N76E	N37W	N43W	N62W
	N02E	N47W	N14W	N14E
	N14E	N09W	N81W	N28E
	N48W	N13E	N09W	N47E
	N09E	N15E	N12E	N52E
	N16E	N32E	N12W	N12E
	N41E	N49W	N47W	
	N60W	N52W	N43W	
	N71W	N41W	N58E	
	N04W	N09W	N28E	
	N12W	N56W	N12E	
	N52W	N05W		
		N49W		
		N11E		