The Digital Michelangelo Project

and the

Forma Urbis Romae Project

Marc Levoy
Computer Science Department
Stanford University

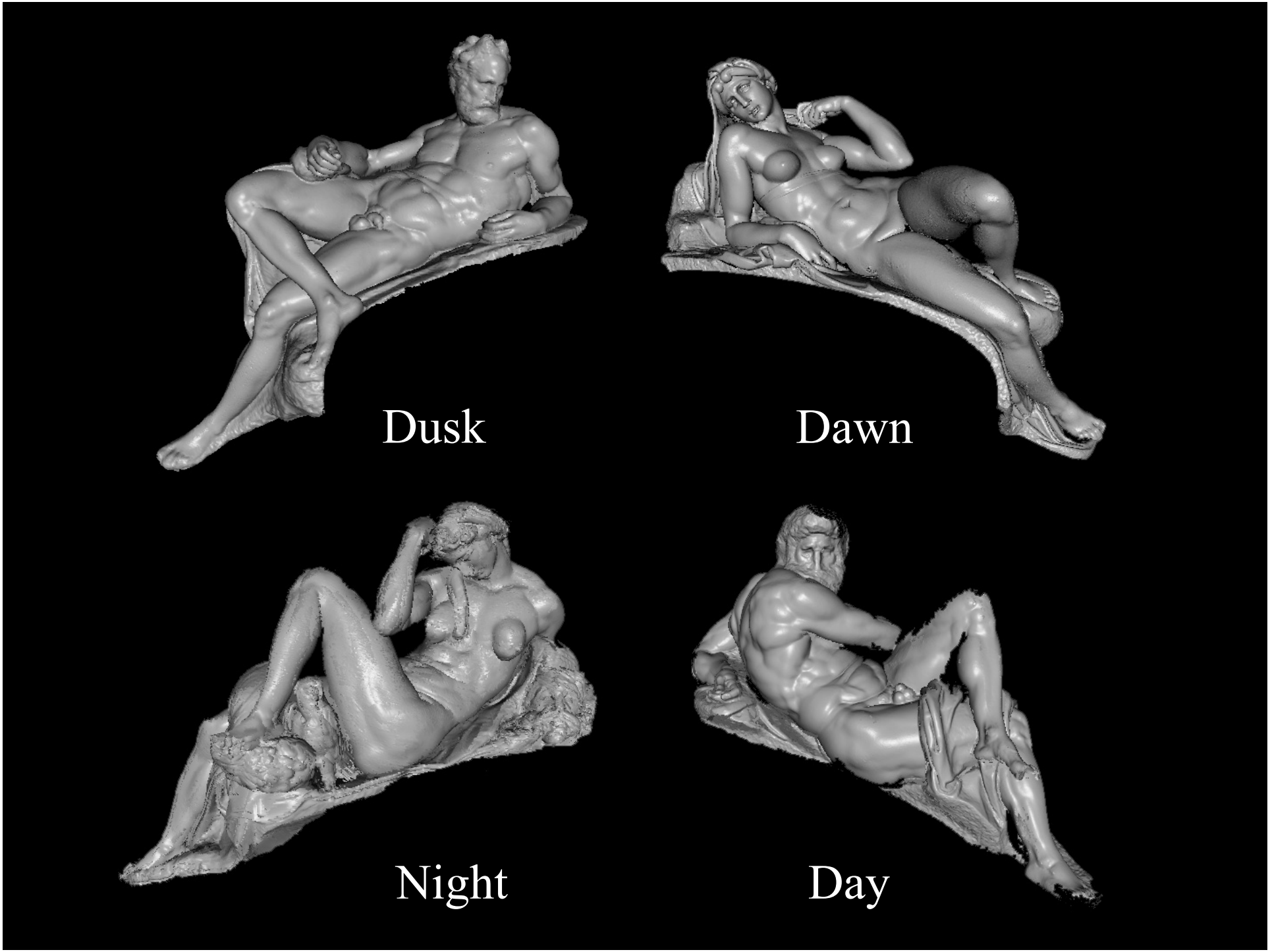
Executive summary

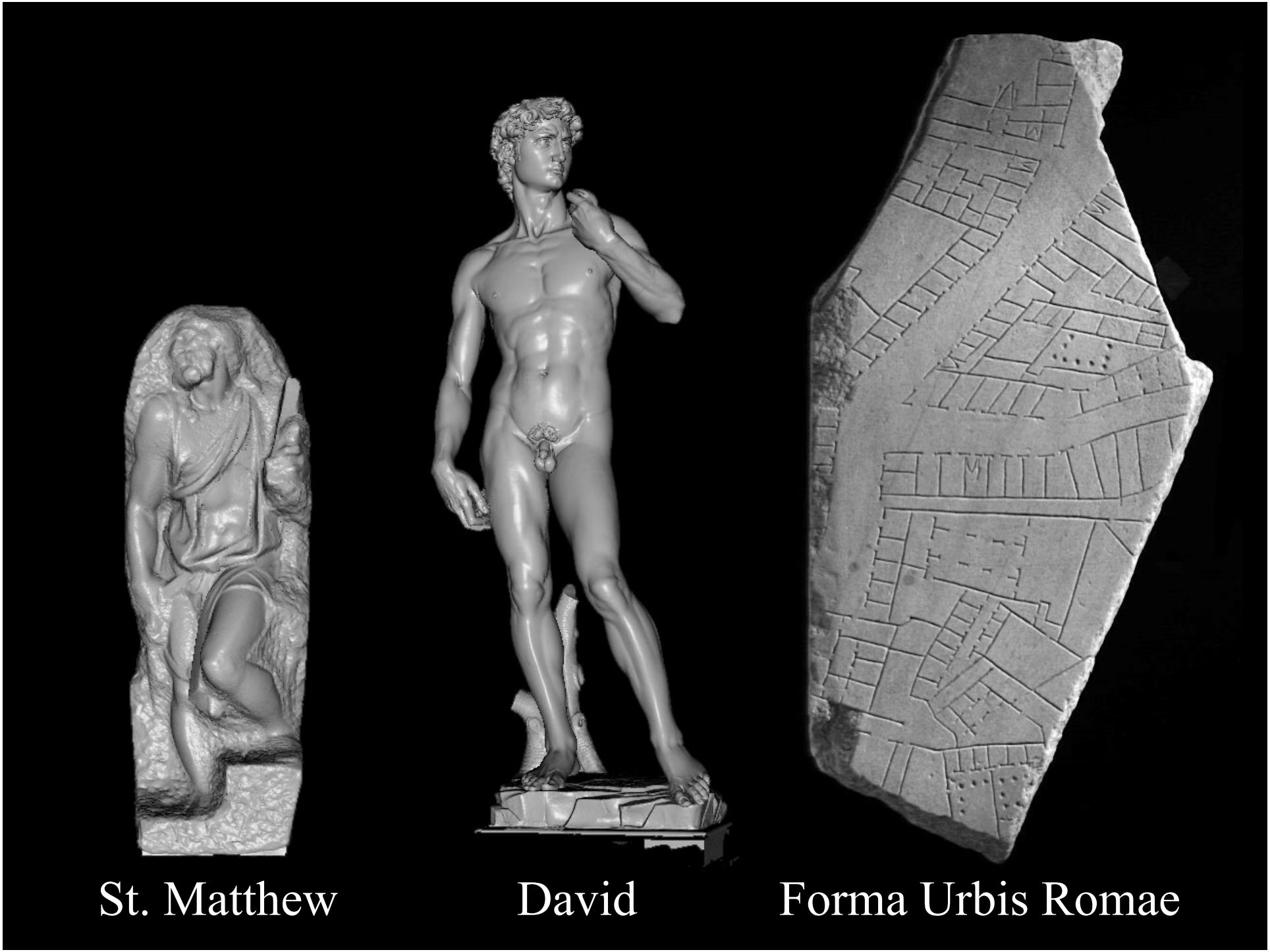
Atlas

Awakening

Bearded

Youthful


Dusk
Dawn
Night
Day


St. Matthew
David
Forma Urbis Romae

Why scan the statues of Michelangelo?

Motivations

- push 3D scanning technology
- tool for art historians and conservators
- lasting archive

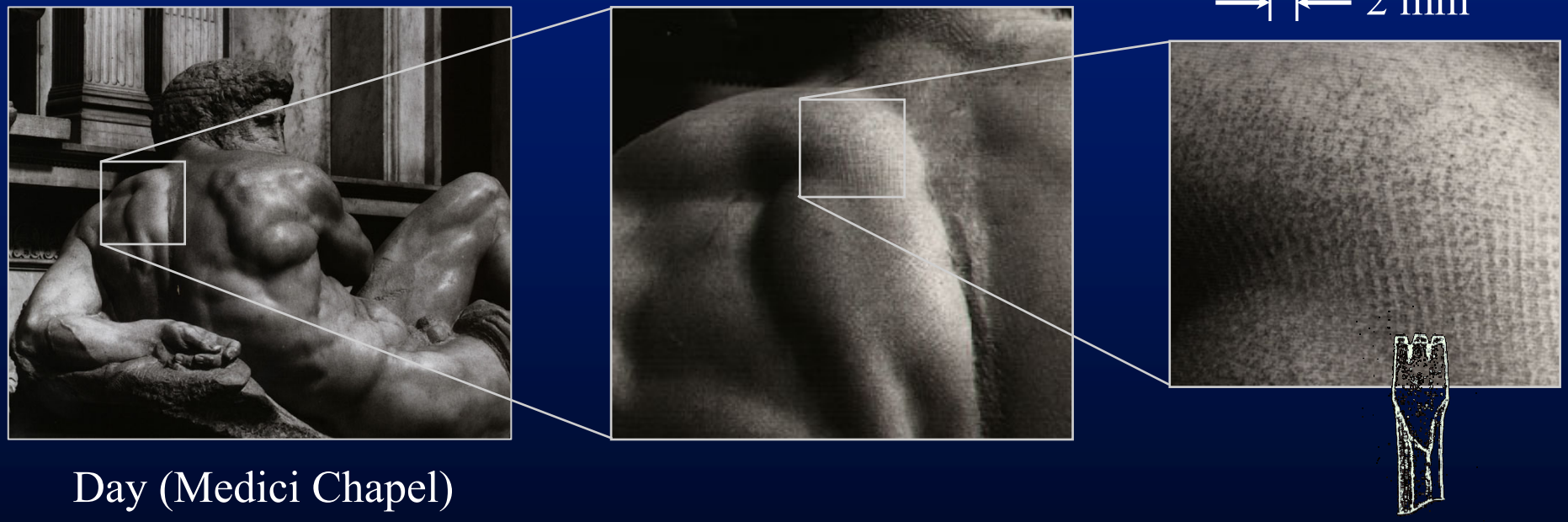
Technical goals

- scan a big statue → 5 meters
- capture chisel marks → 1/4 mm

→ 20,000:1

$20{,}000^2$
≈ 1 billion

Why capture chisel marks?

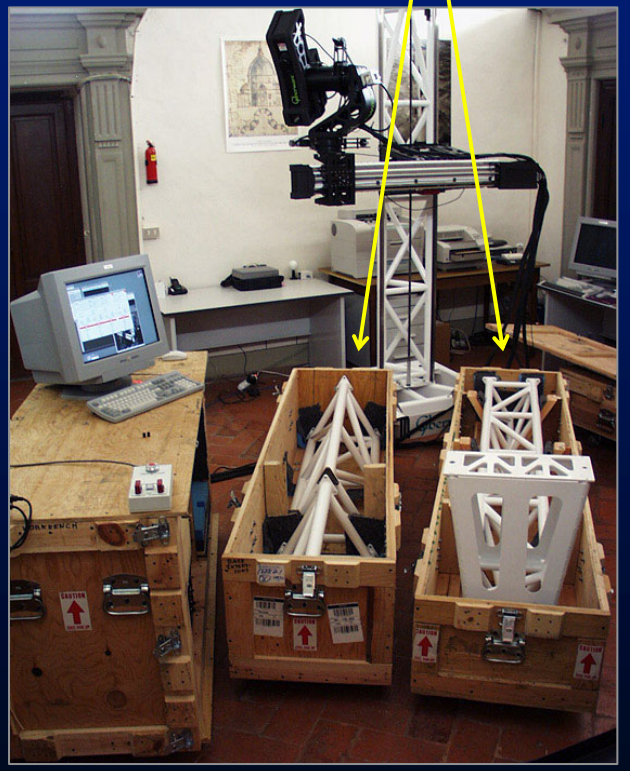


Day (Medici Chapel)

Scanner design

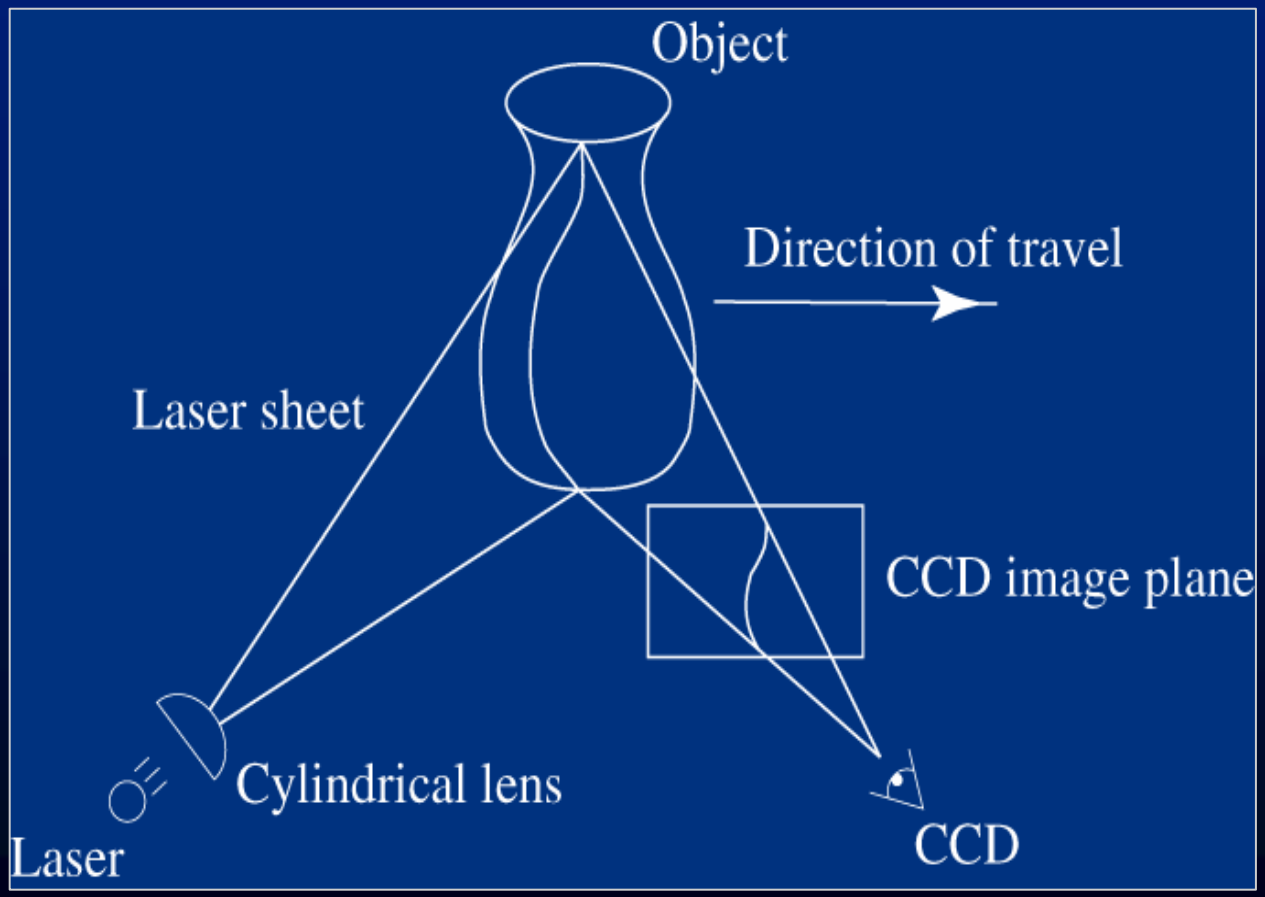
4 motorized axes

truss extensions
for tall statues



laser, range camera,
white light, and color camera

Laser triangulation rangefinding

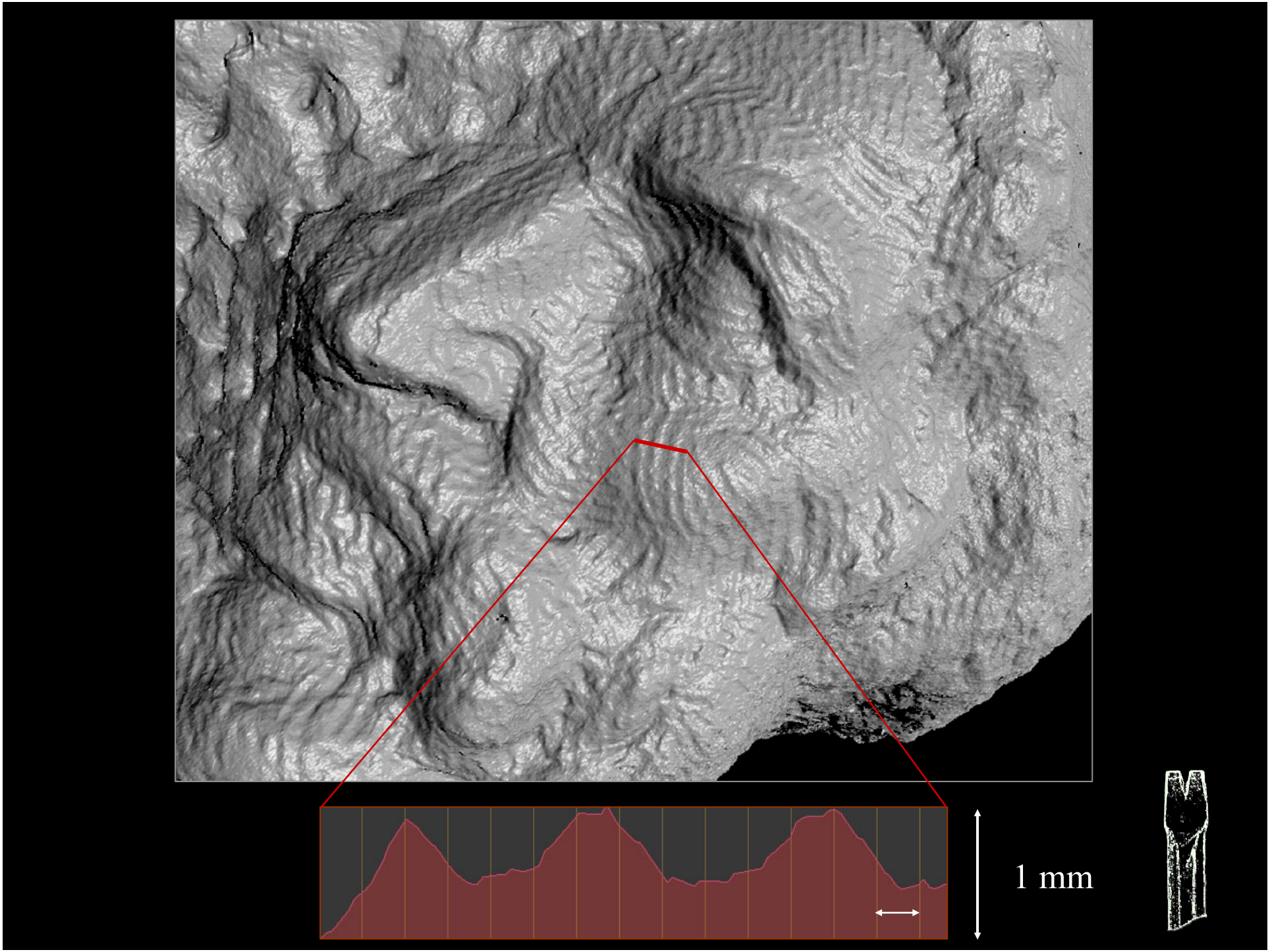


Scanning St. Matthew

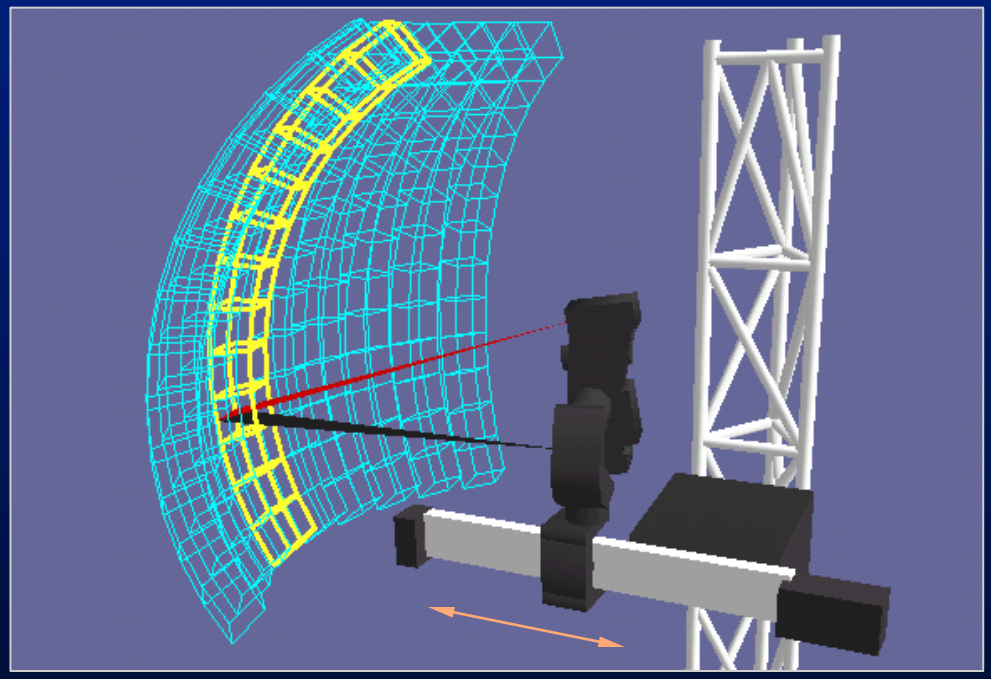
working in
the museum

scanning
geometry

scanning
color


1 mm

Scanning a large object



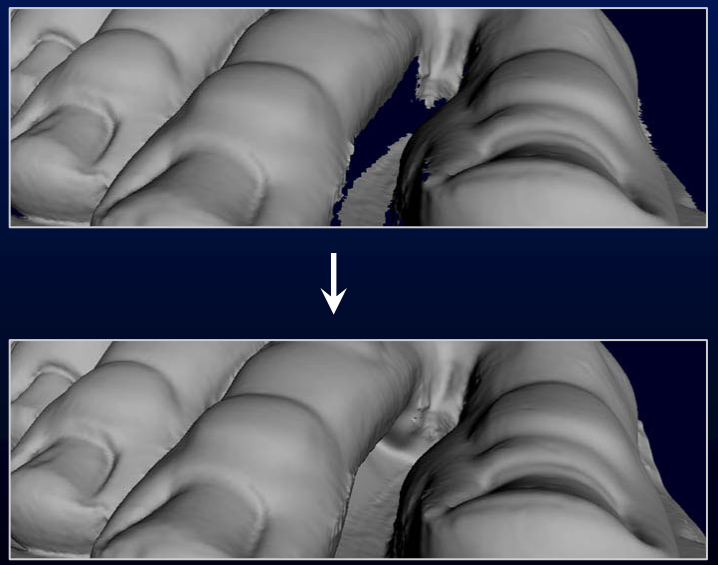
- calibrated motions
  - pitch (yellow)
  - pan (blue)
  - horizontal translation (orange)
- uncalibrated motions
  - vertical translation
  - remounting the scan head
  - moving the entire gantry

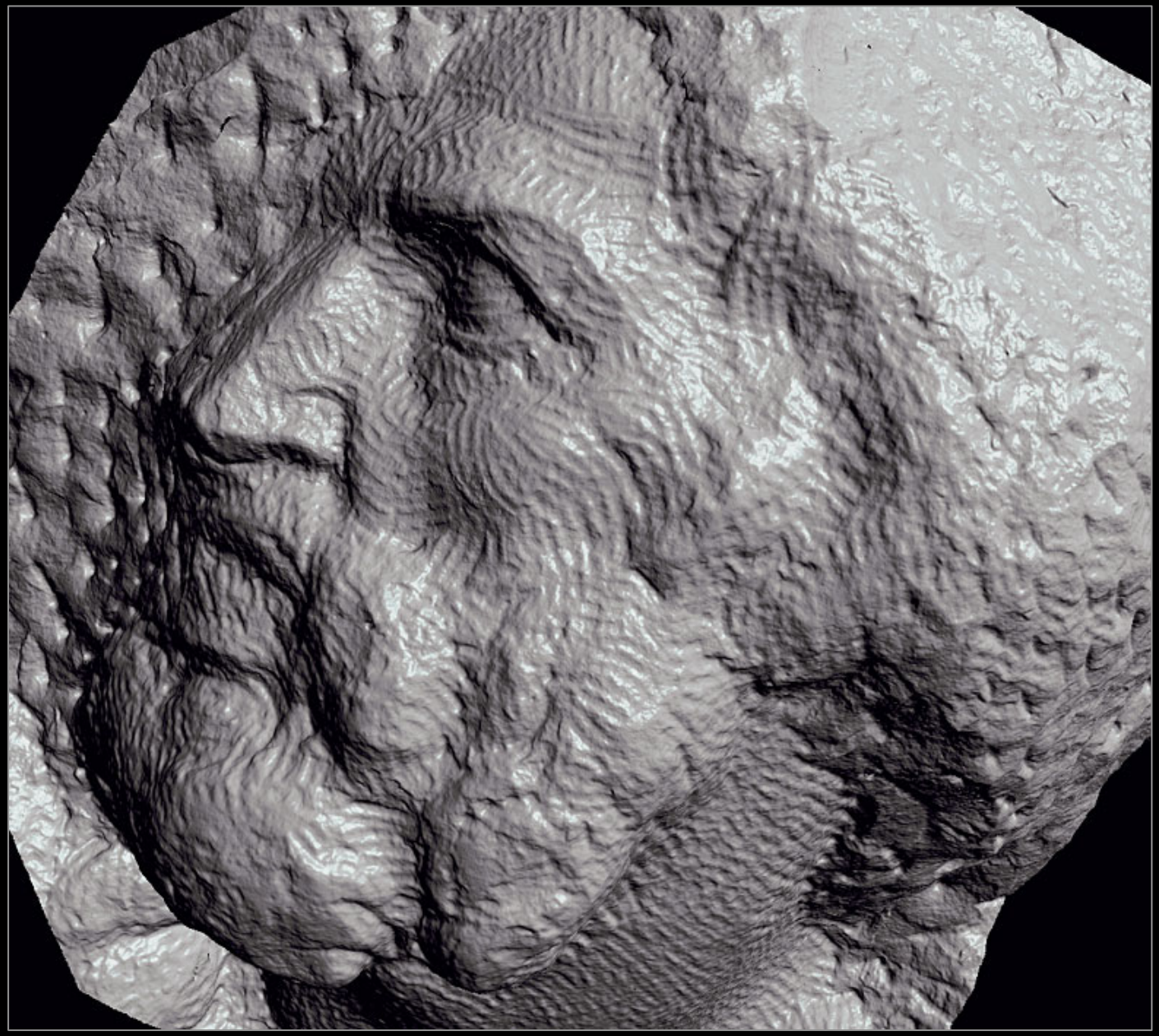
Our scan of St. Matthew

- 104 scans
- 800 million polygons
- 4,000 color images
- 15 gigabytes
- 1 week of scanning

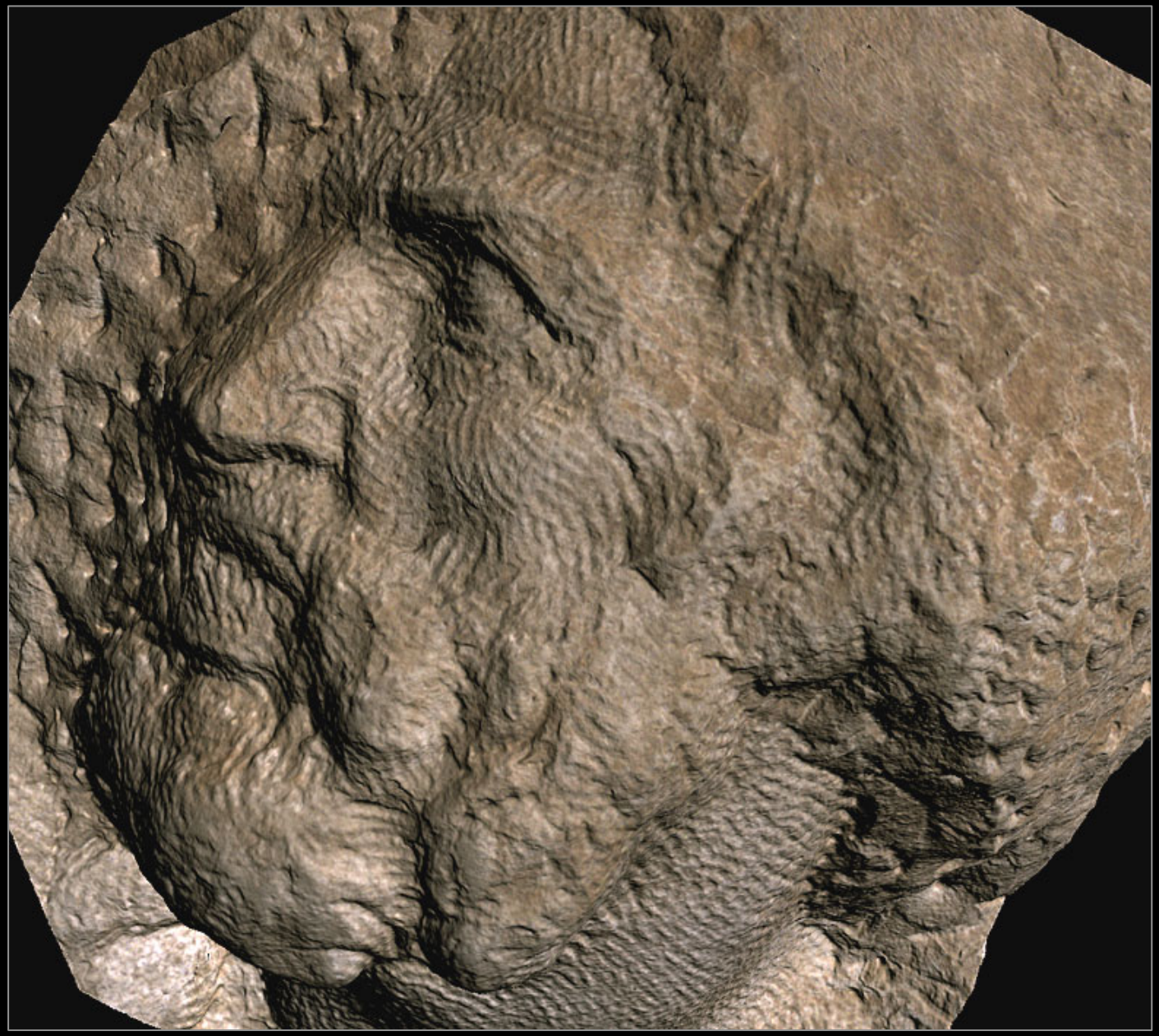
Post-processing pipeline

- steps
  1. aligning the scans
  2. combining aligned scans
  3. filling holes

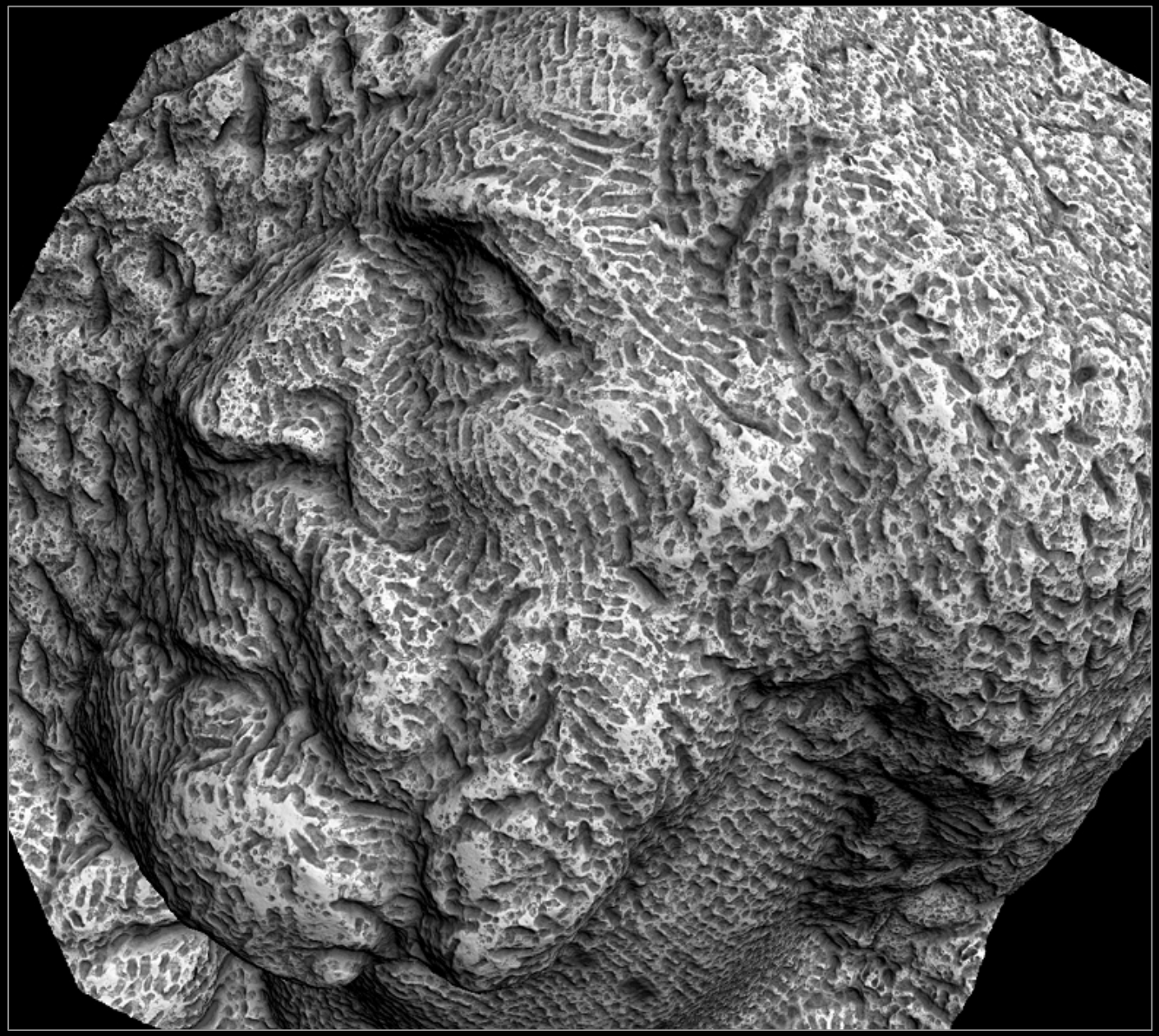




artificial surface reflectance

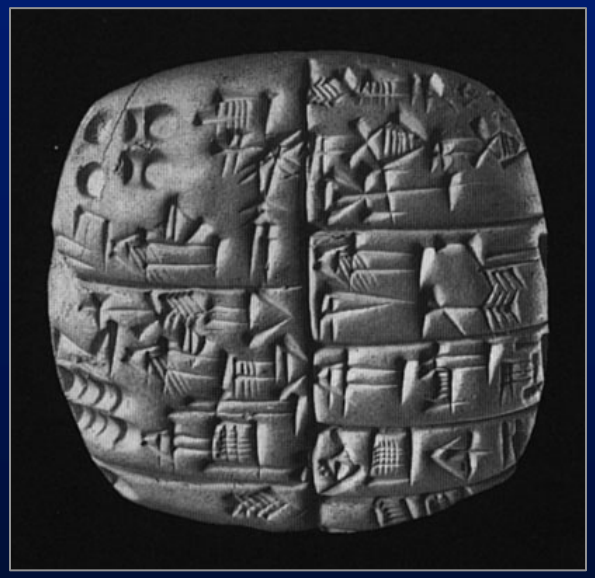


estimated diffuse reflectance



accessibility shading

Visualizing inscribed surfaces
(with application to cuneiform tablets)



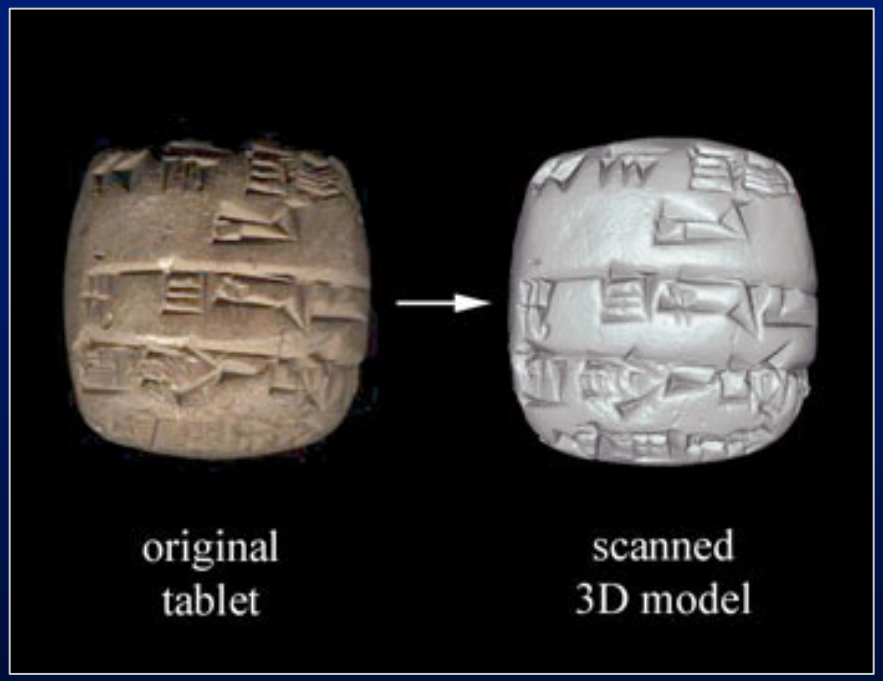
(from Nissen, Damerow, Englund)

- a photograph can only show one side of a tablet at a time
  - hard to show tablet edges
- raking illumination favors strokes of one orientation
  - need multiple photographs

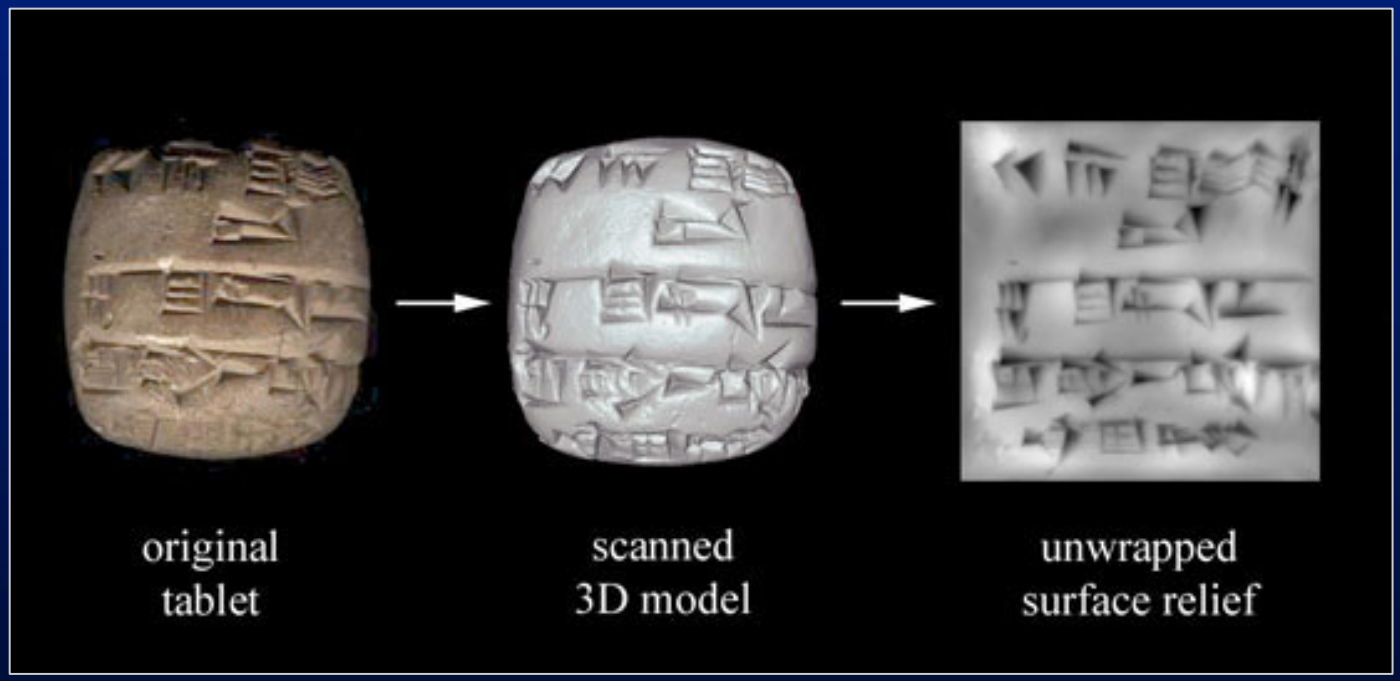
Our processing pipeline

- UR III dynasty (2100 B.C.)

Our processing pipeline

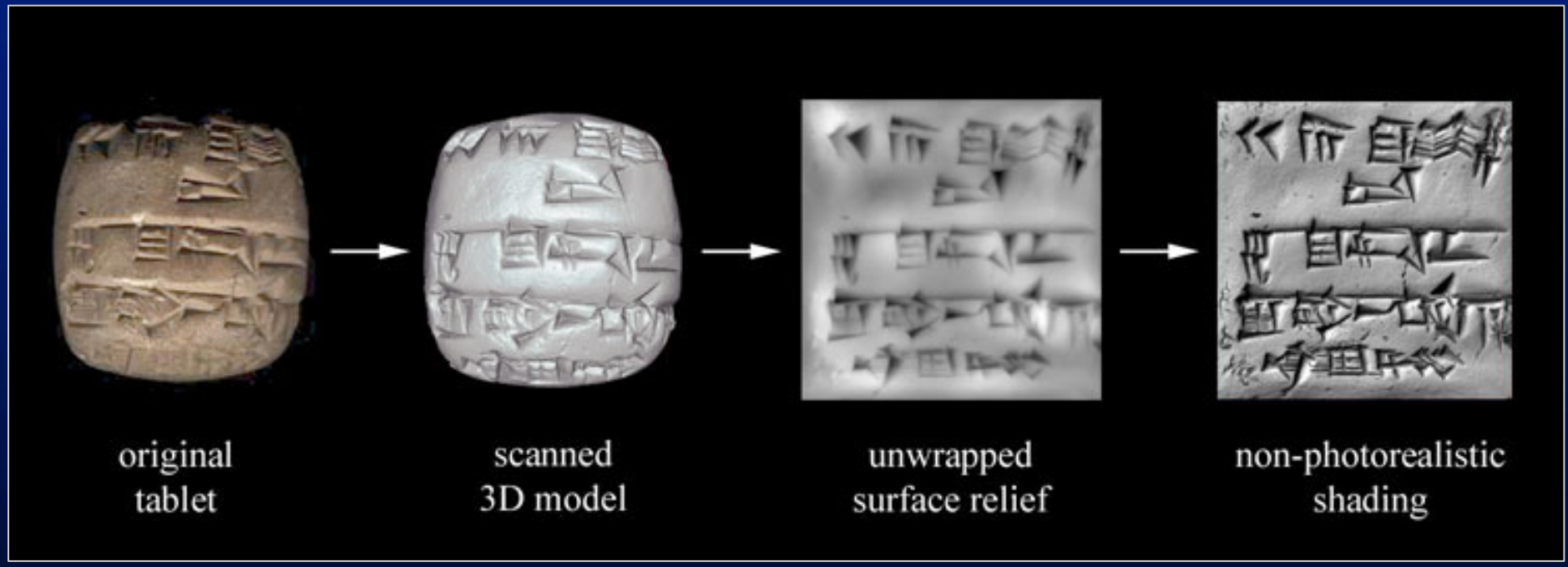


Our processing pipeline

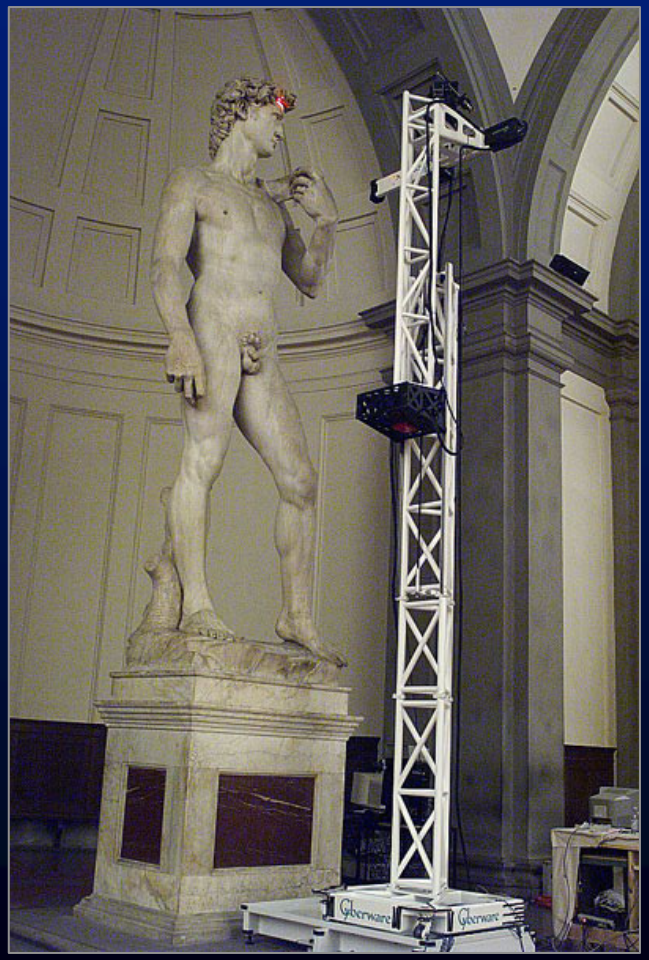


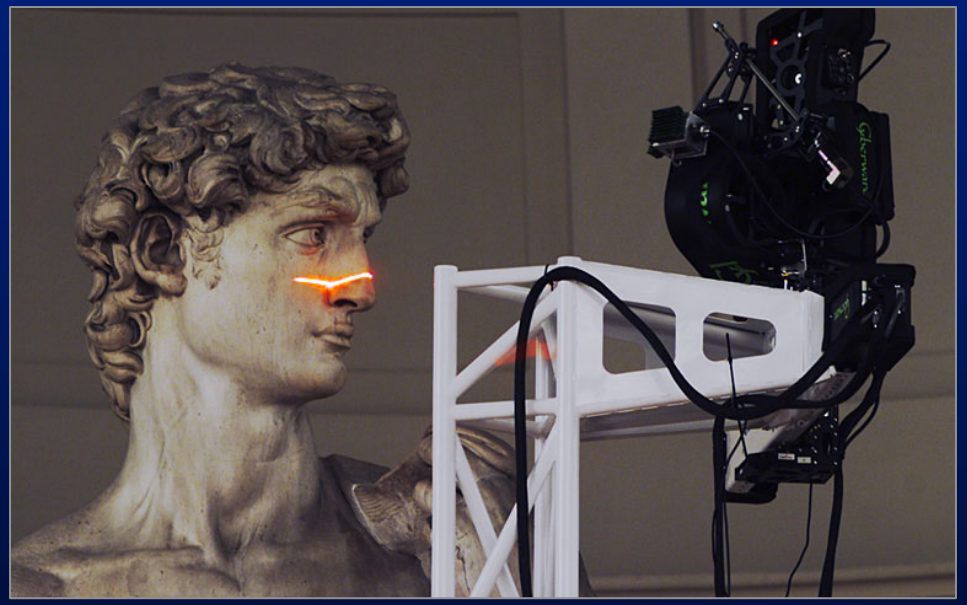
1. fit a curved surface patch to the curved tablet
2. error in fit $\rightarrow$ relief map

Our processing pipeline



Scanning the David

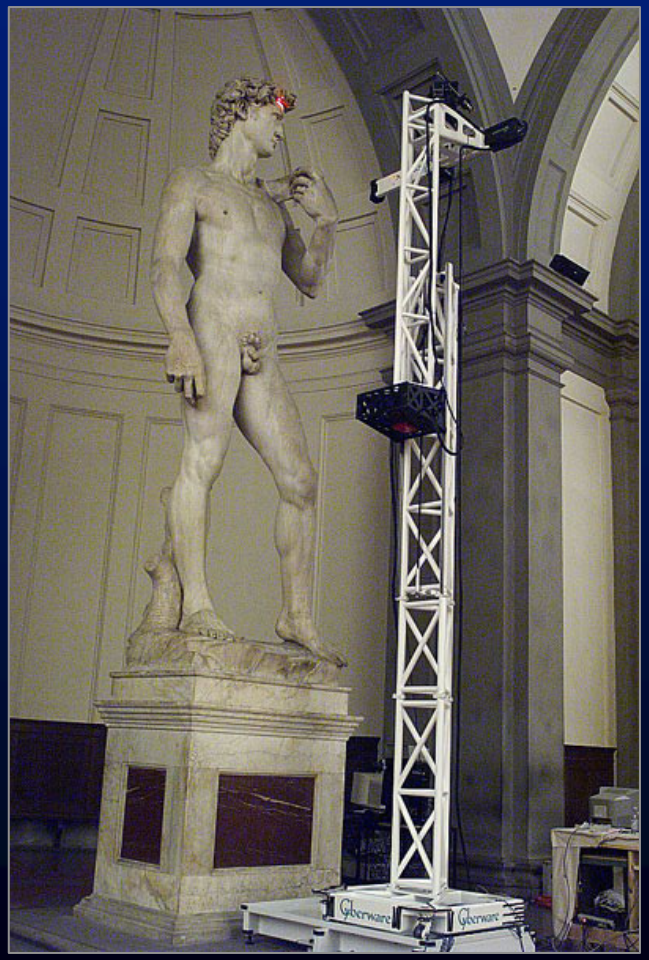




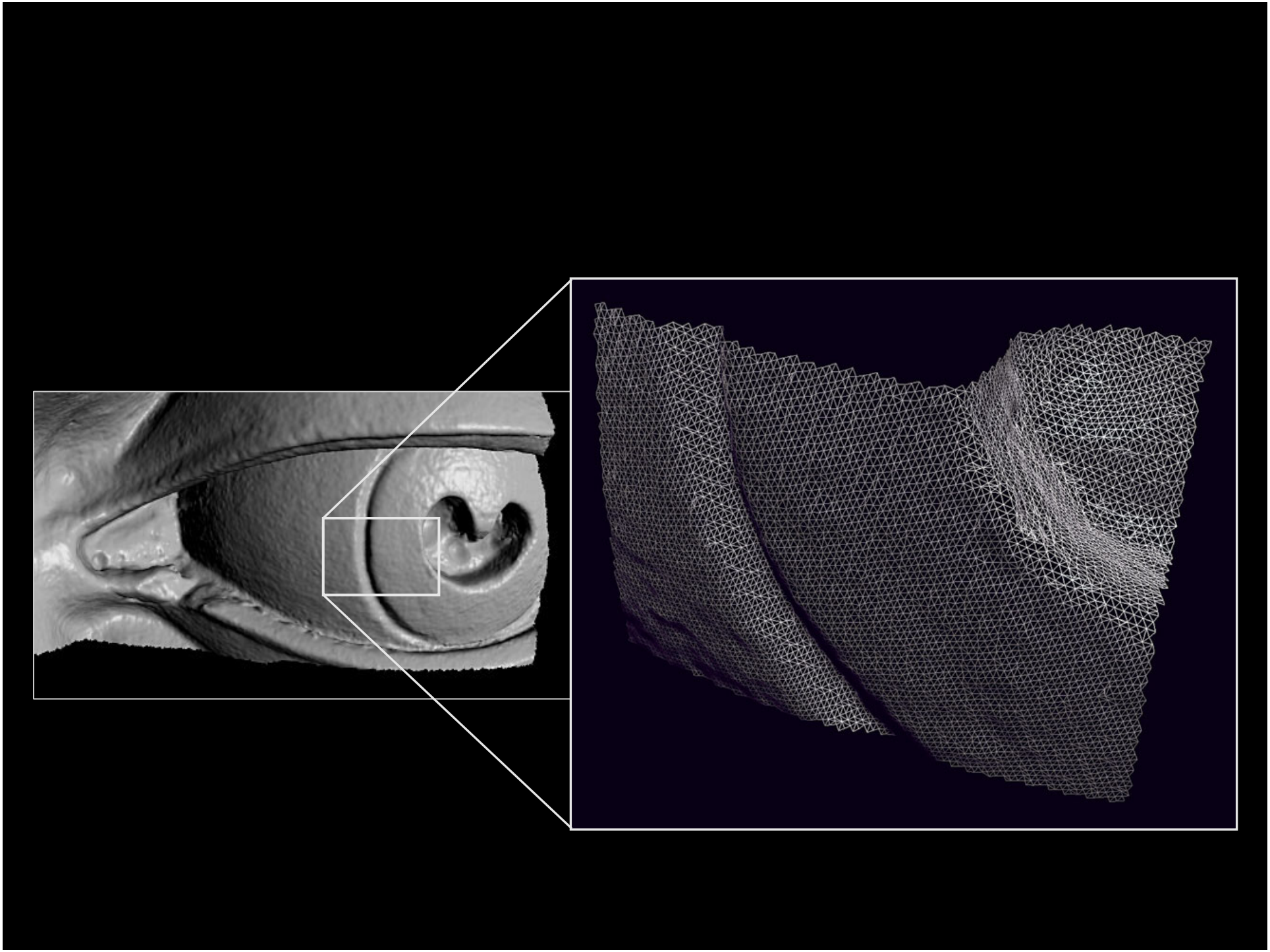
height of gantry: 7.5 meters

weight of gantry: 800 kilograms

Scanning the David



- 480 individually aimed scans
- 2 billion polygons
- 7,000 color images
- 32 gigabytes
- 30 nights of scanning
- 22 people



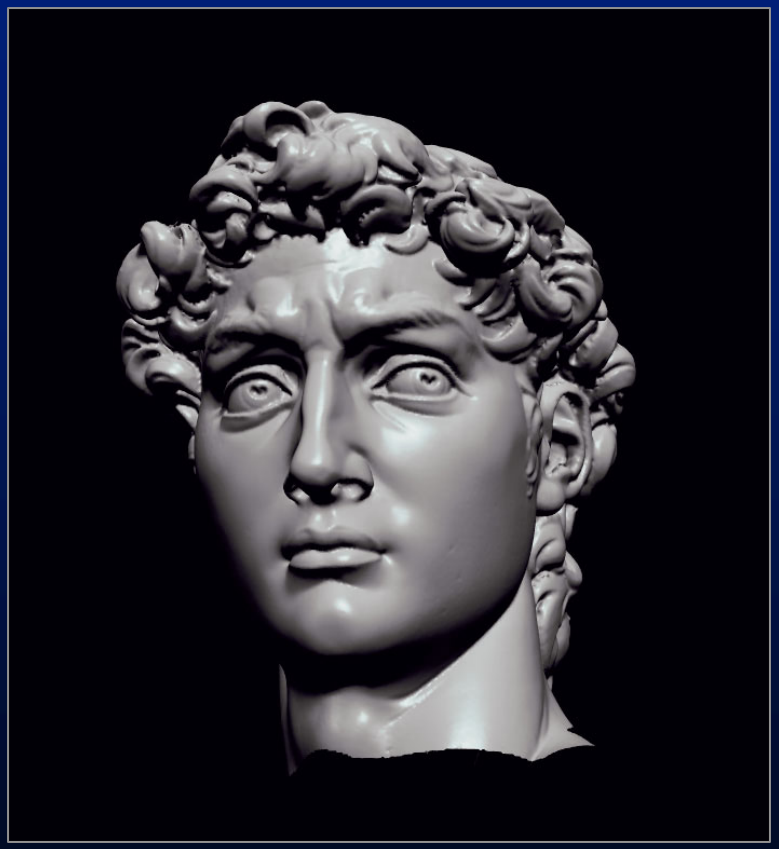
The importance of viewpoint

classic 3/4 view

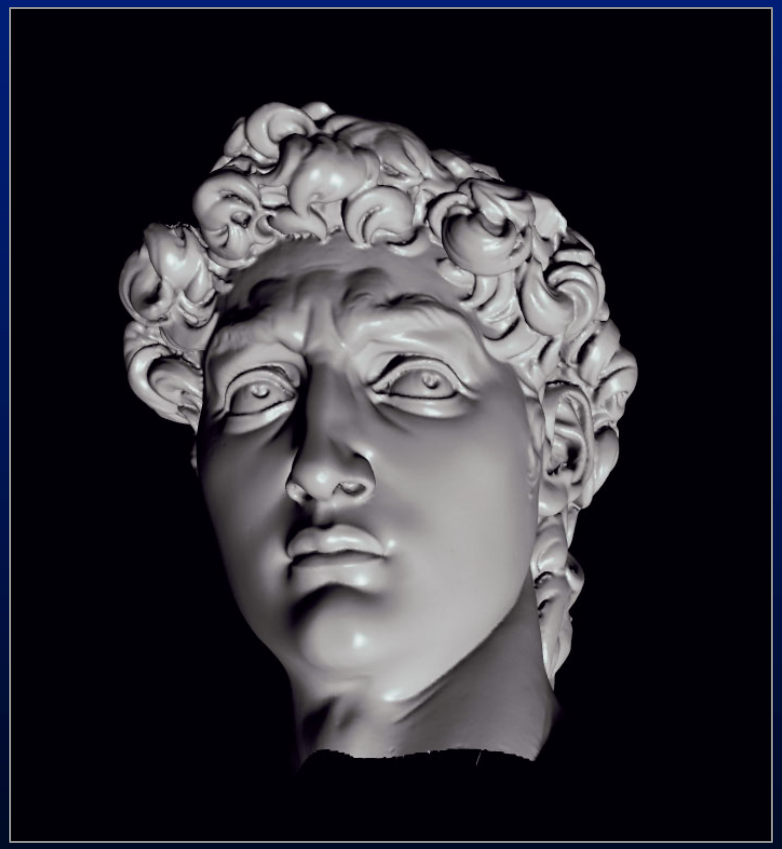
left profile

face-on view

The importance of lighting



lit from above



lit from below

Some uses for these models

- unique views of the statues

A kiosk for viewing 3D models

- PC + graphics card + custom software
- arcade-quality buttons and trackballs
- no touch screen, no menus, no instructions to read

Some uses for these models

- unique views of the statues
- permanent archive

Some uses for these models

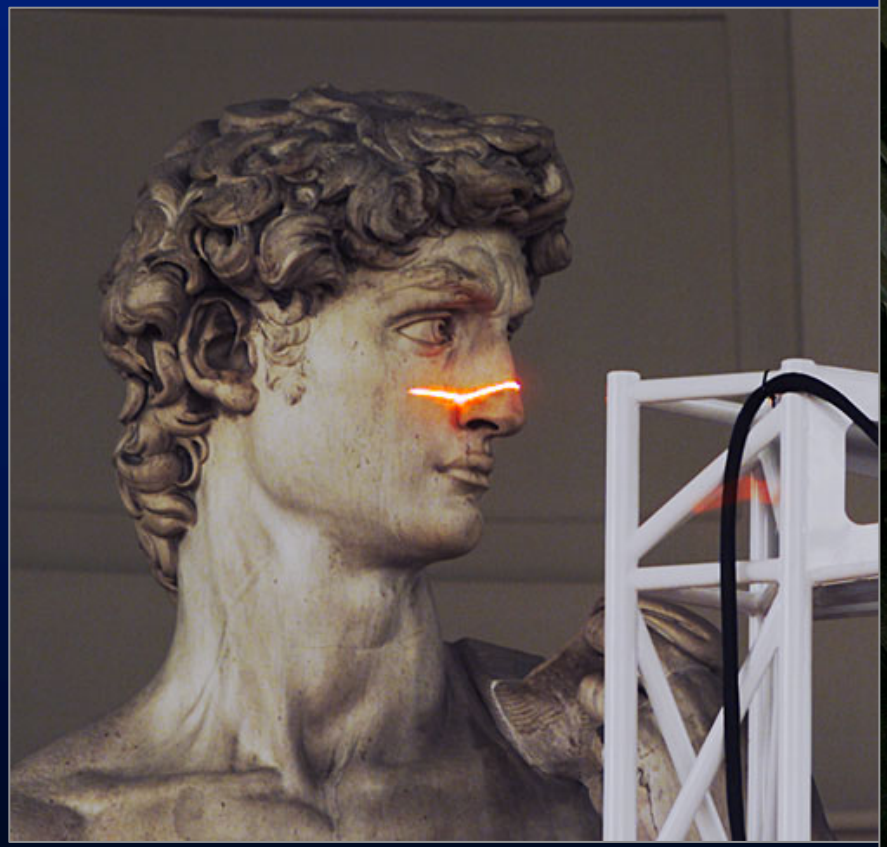
- unique views of the statues
- permanent archive
- physical replicas

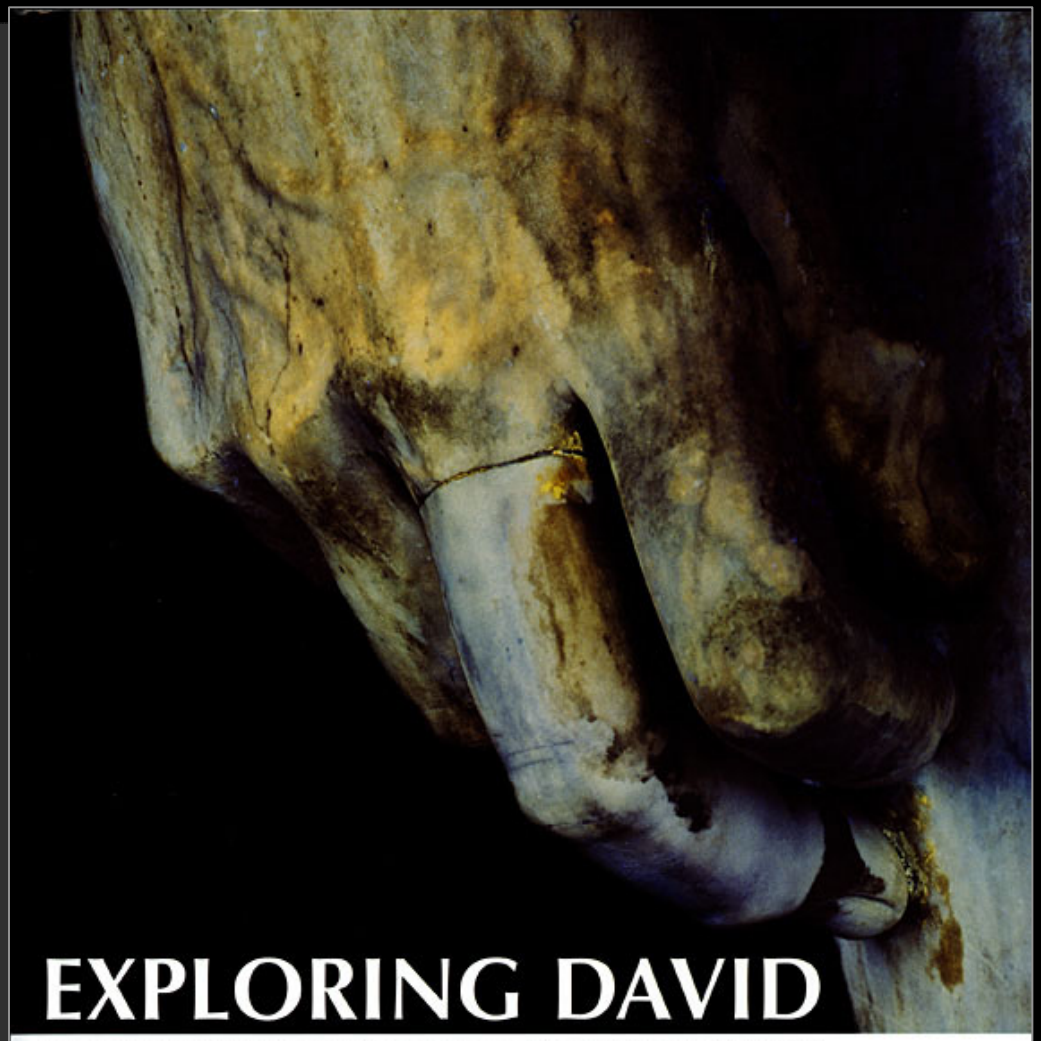
Replica of Michelangelo's David
(20 cm tall)

Some uses for these models

- unique views of the statues
- permanent archive
- physical replicas
- conservation

Cleaning the David



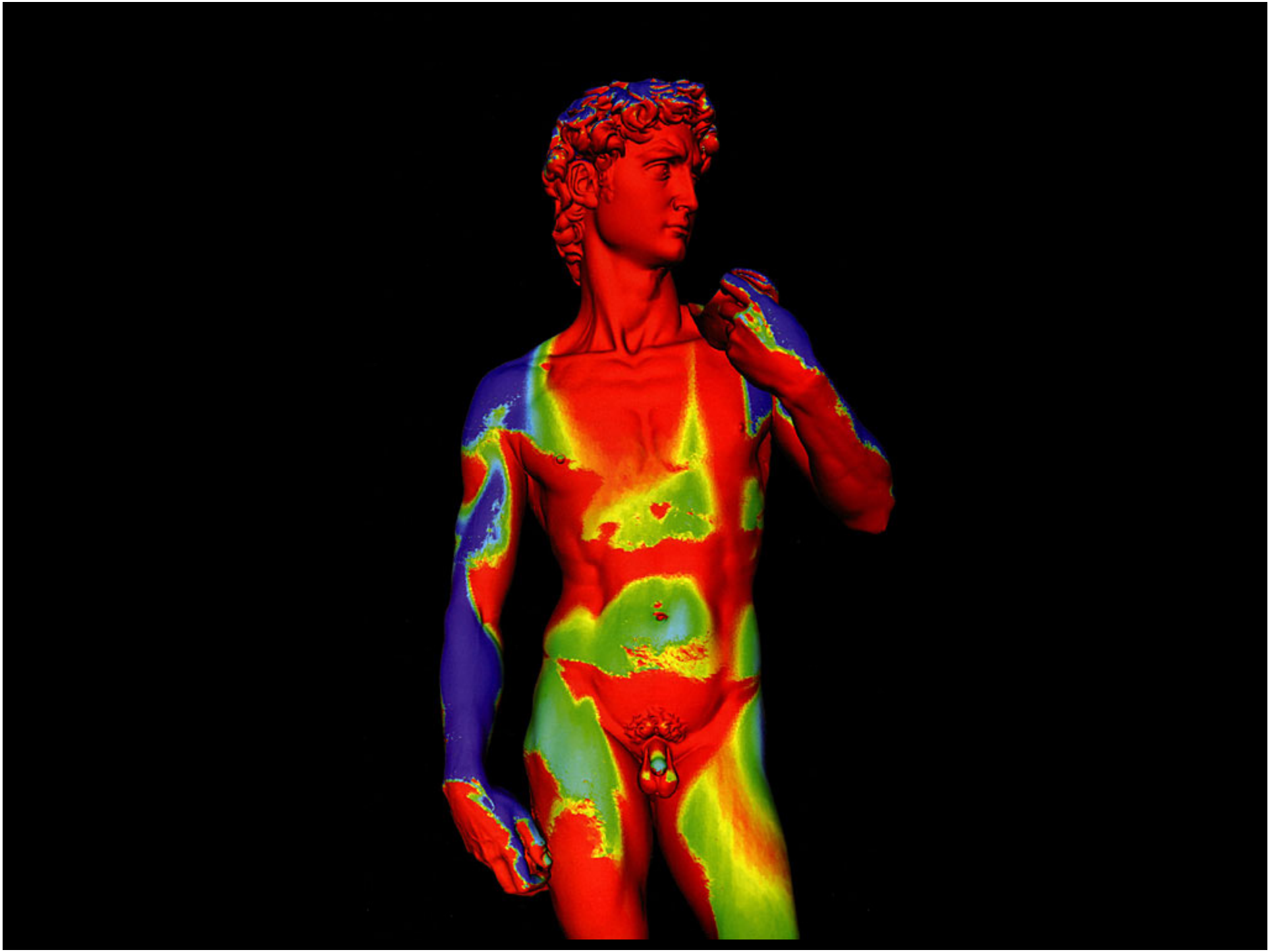


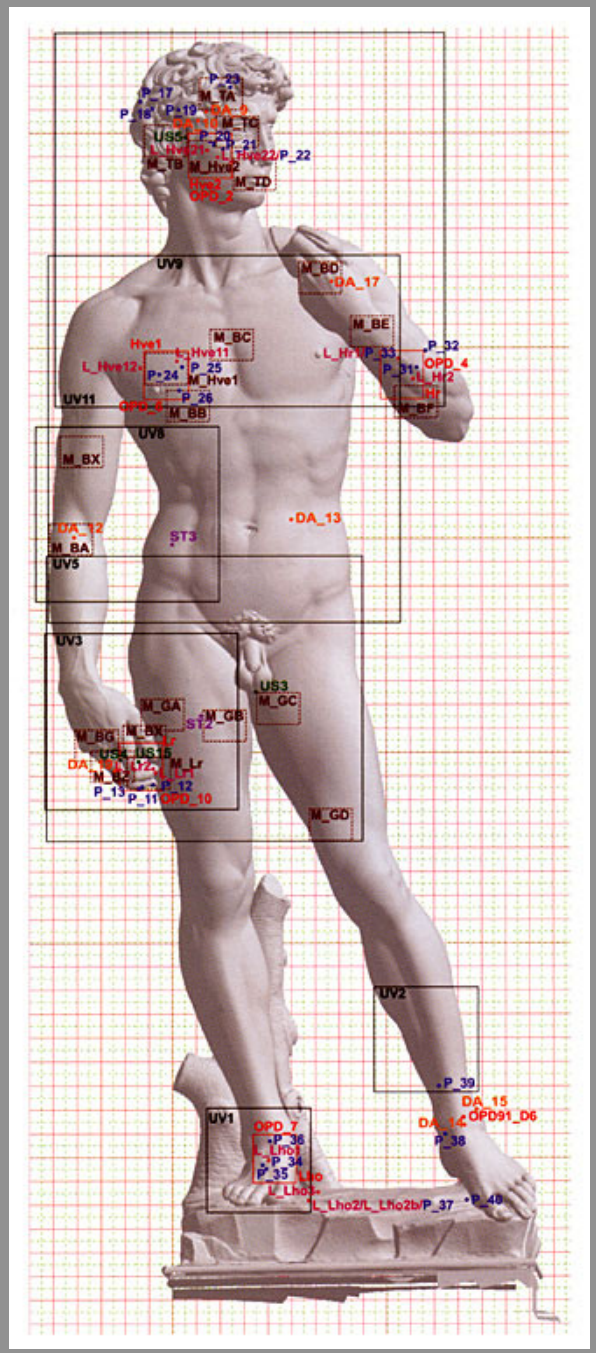
EXPLORING DAVID

DIAGNOSTIC TESTS AND STATE OF CONSERVATION

GIUNTI

FIRENZE MVSEI




P_23
M_TA
P_17
P_18
P_19
DA_9
M_TC
US5
P_20
P_21
L_Hve21
L_Hve22/P_22
M_TB
M_Hve2
Hve2
M_TD
OPD_2
UV9
M_BD
DA_17
M_BE
Hve1
M_BC
L_Hve11
L_Hve12
P_24
P_25
M_Hve1
L_Hr
P_35
P_32
P_31
OPD_4
L_Hr2
Hr
M_BF
P_26
UV11
M_BB
UV8
M_BX
DA_12
M_BA
ST3
DA_13
UV5
UV3
US3
M_GC
M_GA
M_GB
ST2
M_BG
M_BX
US4
US15
M_Lr
P_13
P_12
P_11
OPD_10
M_GD
UV2
P_39
DA_15
OPD91_D6
DA_14
P_38
UV1
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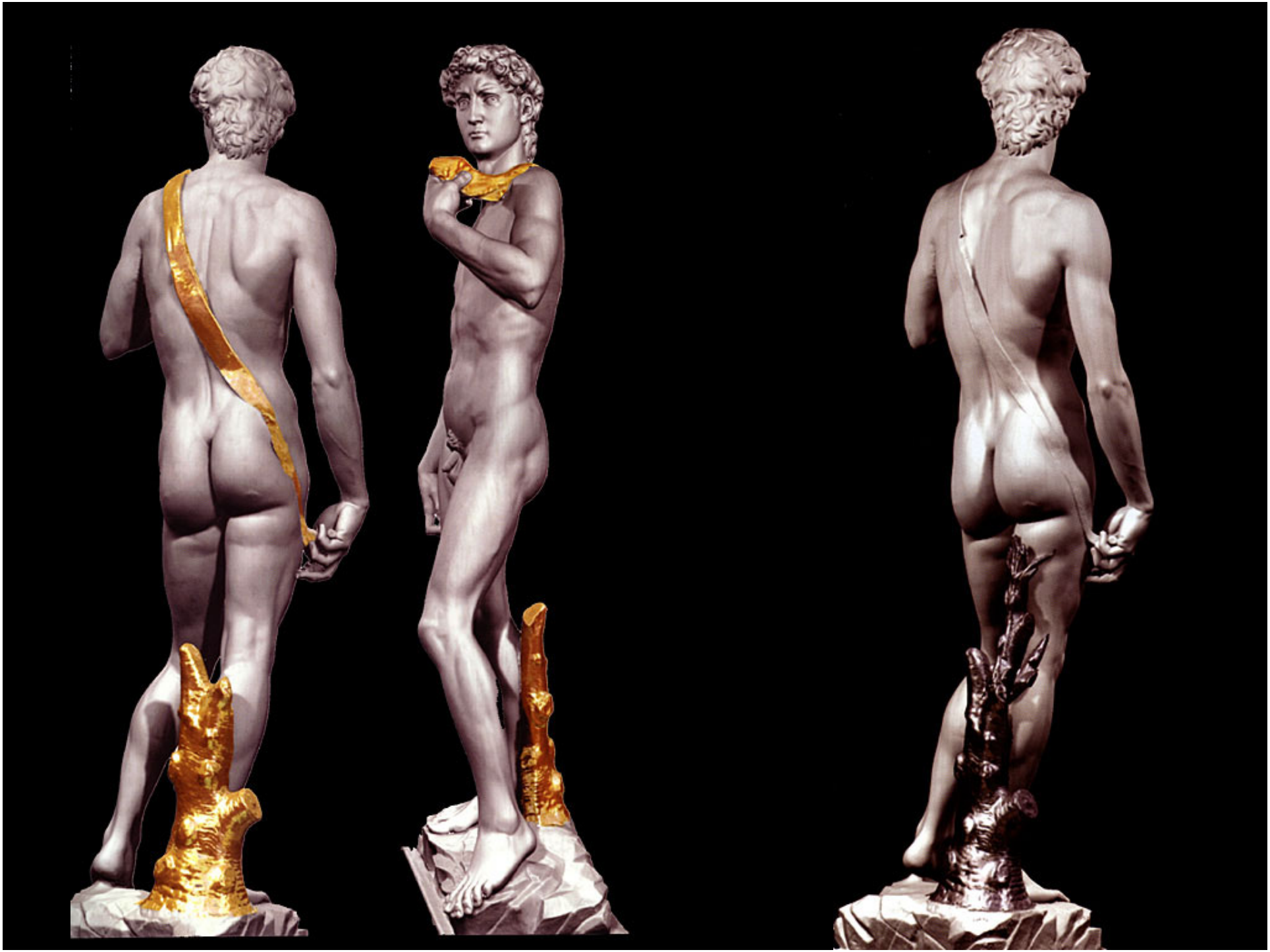
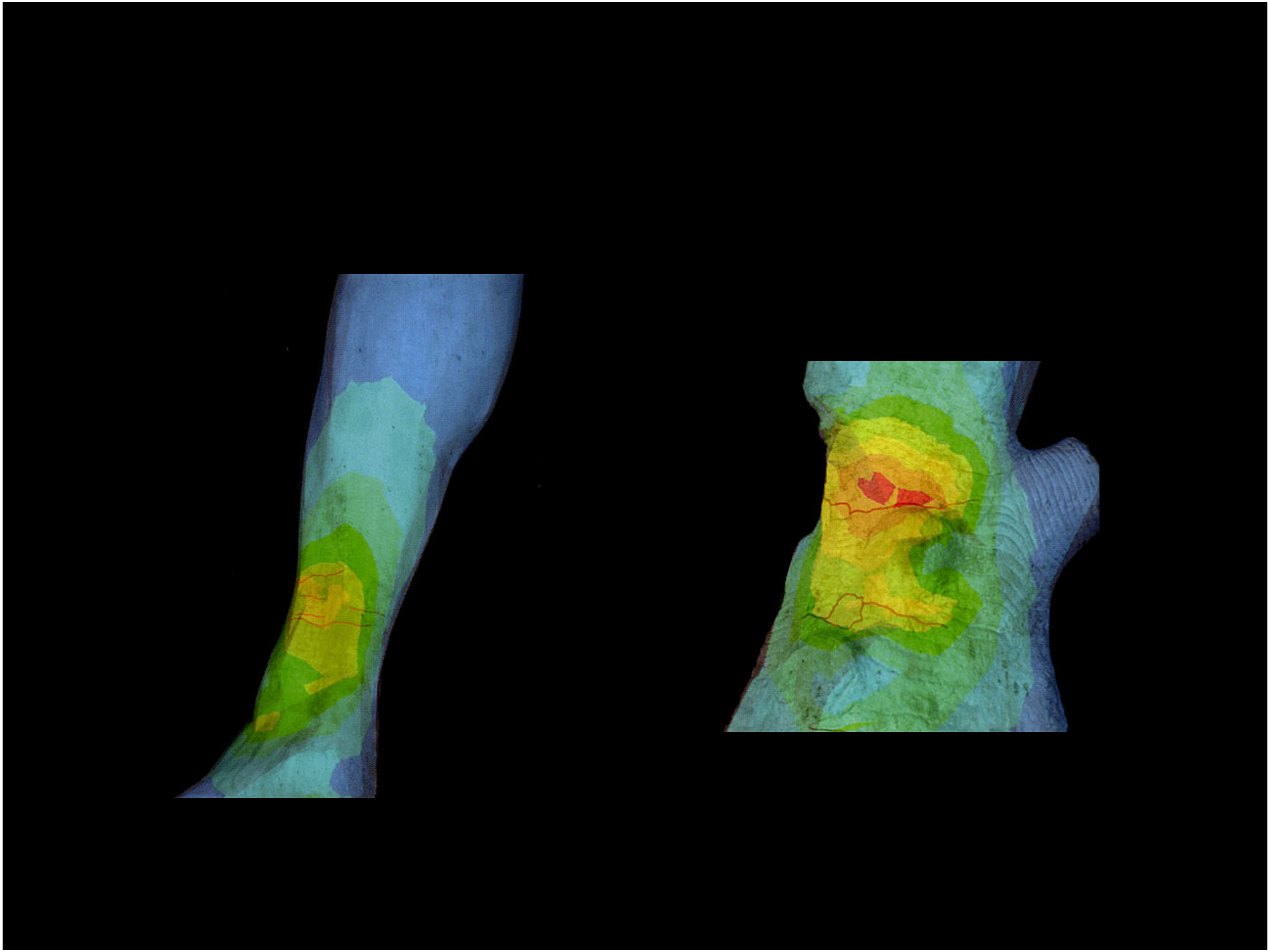
L_Lho3
L_Lho2/L_Lho2b/P_37
P_48





Digital Michelangelo Project
Grand Catalog

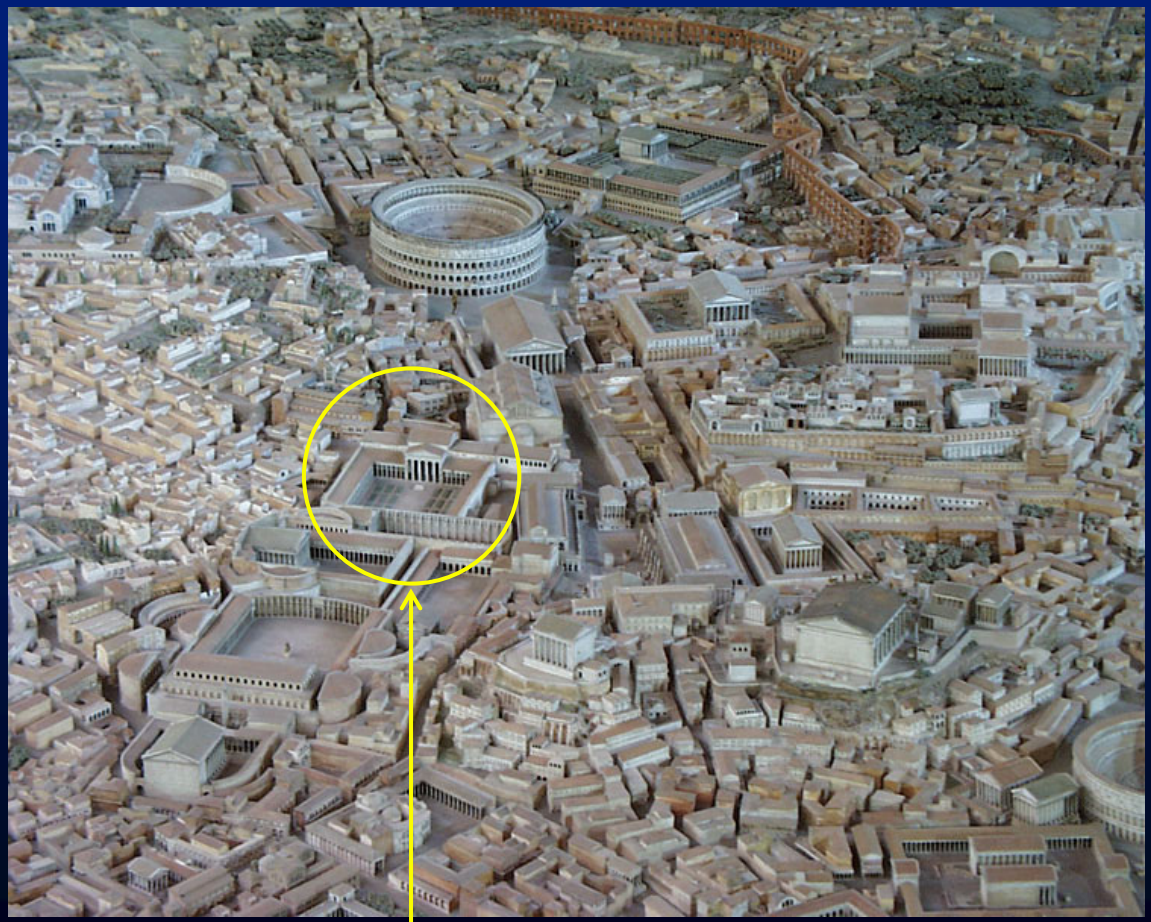
The Digital Michelangelo Project Archive

Digital Michelangelo Project Main Page
Help file

Statue Name	Atlas	Awakening	Barbuto
Rendering			
README	Atlas README		
Calibration	old.calib	default	old.calib
Raw SD Data	atlas-sd-1.tar.gz (215 MB) atlas-sd-2.tar.gz (279 MB) atlas-sd-3.tar.gz (184 MB) atlas-sd-4.tar.gz (116 MB)	awakening-sd-1.tar.gz (248 MB) awakening-sd-2.tar.gz (276 MB) awakening-sd-3.tar.gz (102 MB) awakening-sd-4.tar.gz (78.8 MB)	barbuto-sd-1.tar.gz (224 MB) barbuto-sd-2.tar.gz (222 MB) barbuto-sd-3.tar.gz (132 MB)
Modelmaker Data	atlas-modelmaker-1.tar.gz (261 MB) atlas-modelmaker-2.tar.gz (411 MB) atlas-modelmaker-3.tar.gz (294 MB) atlas-modelmaker-4.tar.gz (340 MB) atlas-modelmaker-5.tar.gz (177 MB) atlas-modelmaker-6.tar.gz (241 MB)	awakening-modelmaker-1.tar.gz (230 MB) awakening-modelmaker-2.tar.gz (146 MB)	barbuto-modelmaker-1.tar.gz (186 M barbuto-modelmaker-2.tar.gz (187 M

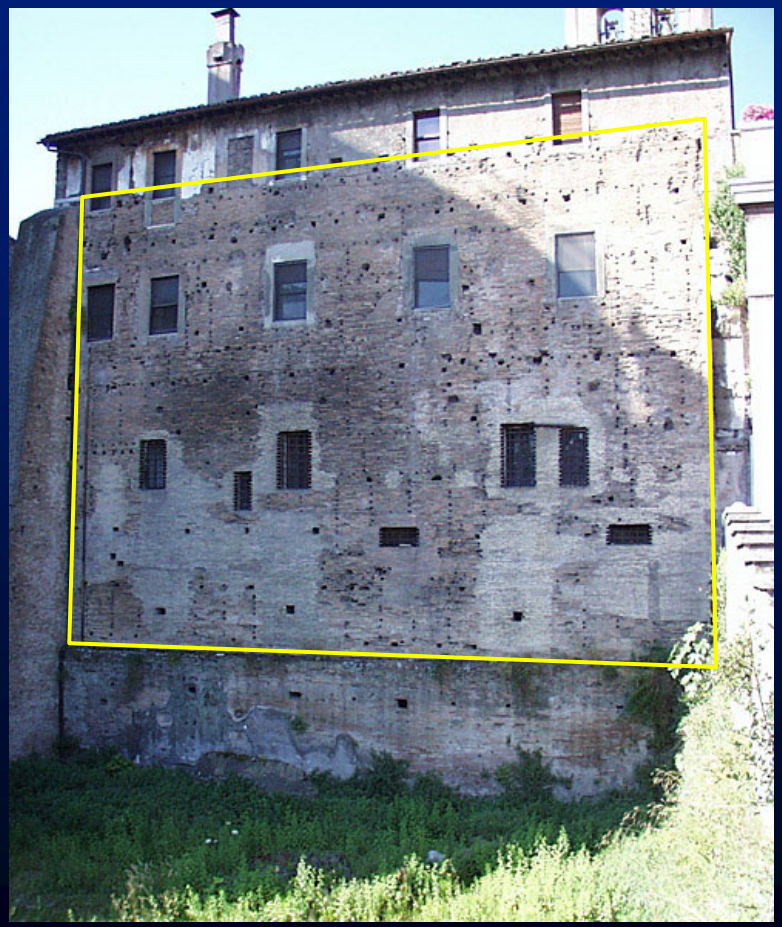
Solving the puzzle of the Forma Urbis Romae

Rome, circa 200 AD



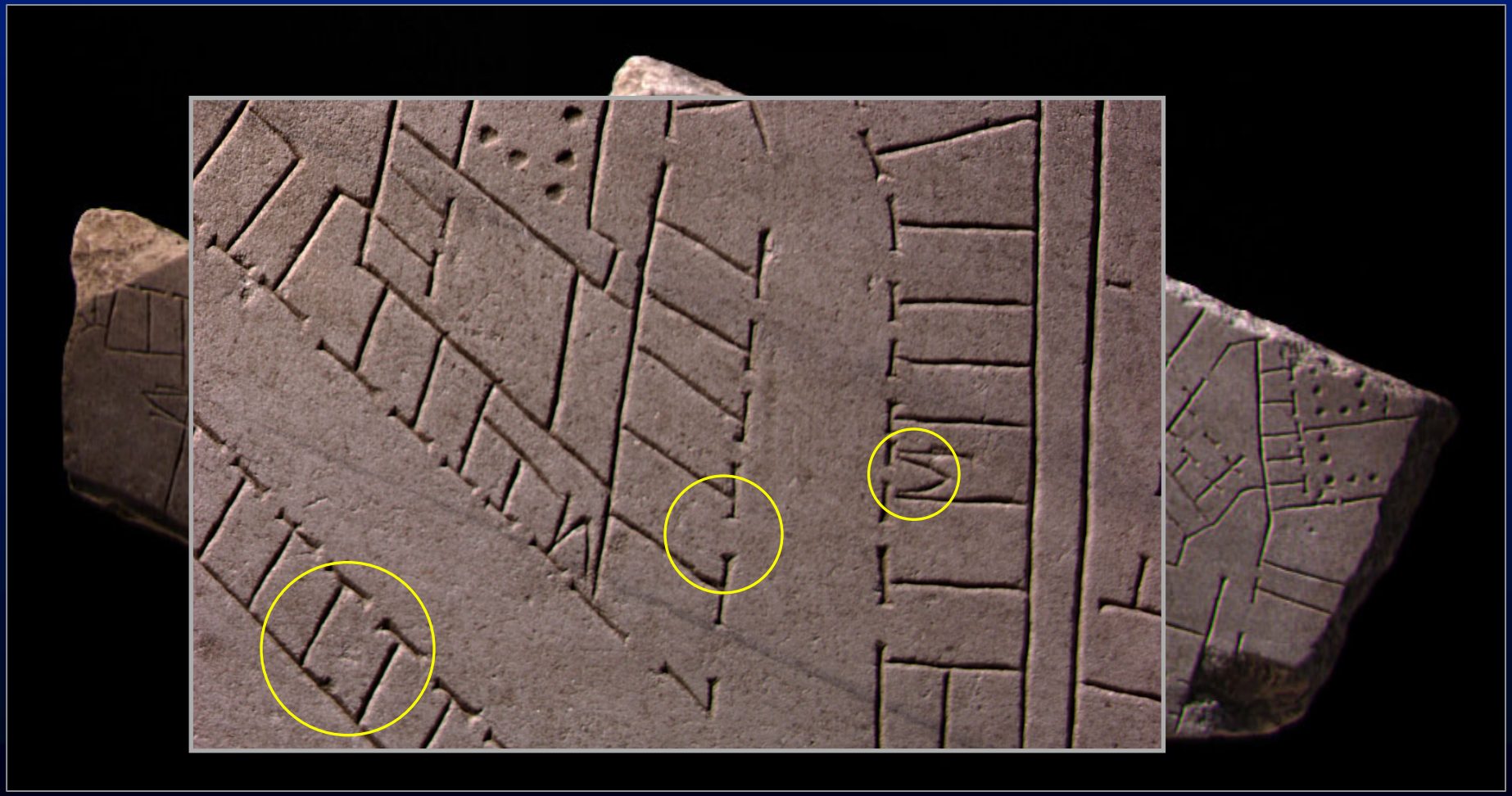
Forum Pacis

Forma Urbis Romae
(form of the city of Rome)



- carved 207 A.D.
- 60 wide x 45 feet high
- marble, 4 inches thick
- showed the entire city at 1:240
- most important map of ancient Rome that still exists

Fragment # 010g



Solving the jigsaw puzzle

- 1,186 fragments
  - 200 identified
  - 600 unidentified
  - 400 unincised
- 15% of map remains
  - but strongly clustered
  - 1 out of 3 fragments remain in the central core of the city
- *fitting the remaining pieces together has been an open problem for 500 years*

Scanning the fragments

uncrating...

Scanning the fragments

positioning...

Scanning the fragments

scanning...

Scanning the fragments

aligning...

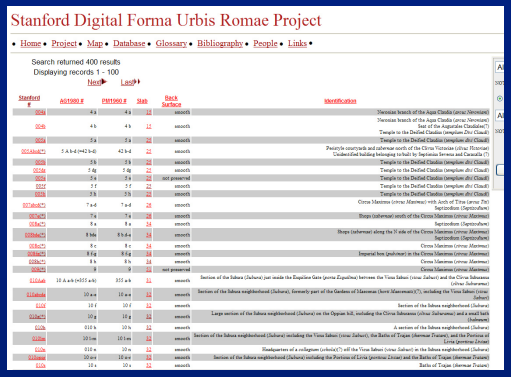
Fragment #642

3D model

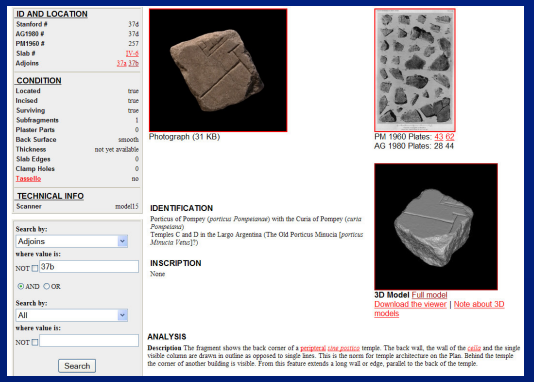
color photograph

Sizes of 3D digital archives

model	polygon count
Americo Vespuccio, commercial model by De Espona	224,000
Trajan's Forum, reconstruction by B. Frischer (UCLA)	1,950,000
Santa Cristina Crypt, Carpignano, laser scan by A. Beraldin (NRC)	12,000,000
Michelangelo's David, laser scan by M. Levoy et al. (Stanford)	56,000,000
1,186 fragments of the FUR	8,000,000,000



Online archive

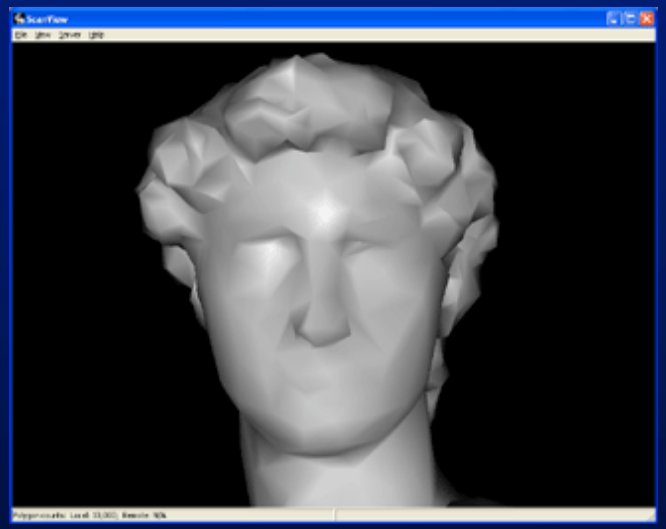


- scholar's version *(http://rockpile.stanford.edu)*
  - viewable and downloadable 3D models
  - high-resolution color photographs
  - requires permission from Stanford and Rome

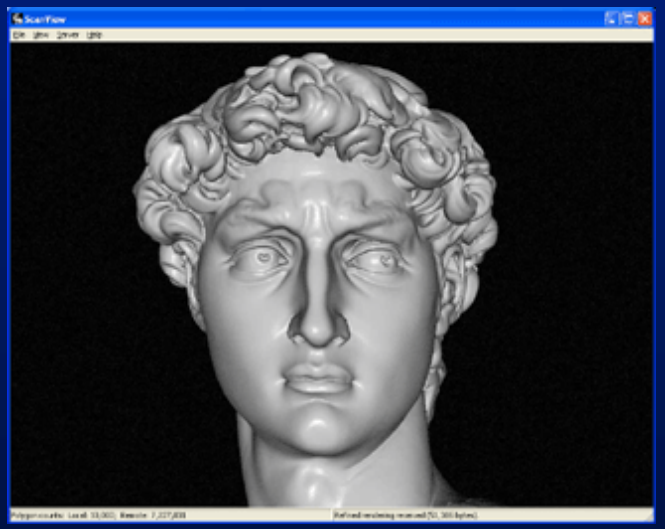
- public version *(http://formaurbis.stanford.edu)*
  - viewable but not downloadable 3D models
  - medium-resolution photographs
  - no license required

ScanView remote rendering system
[Koller, SIGGRAPH 2004]

low-res client model

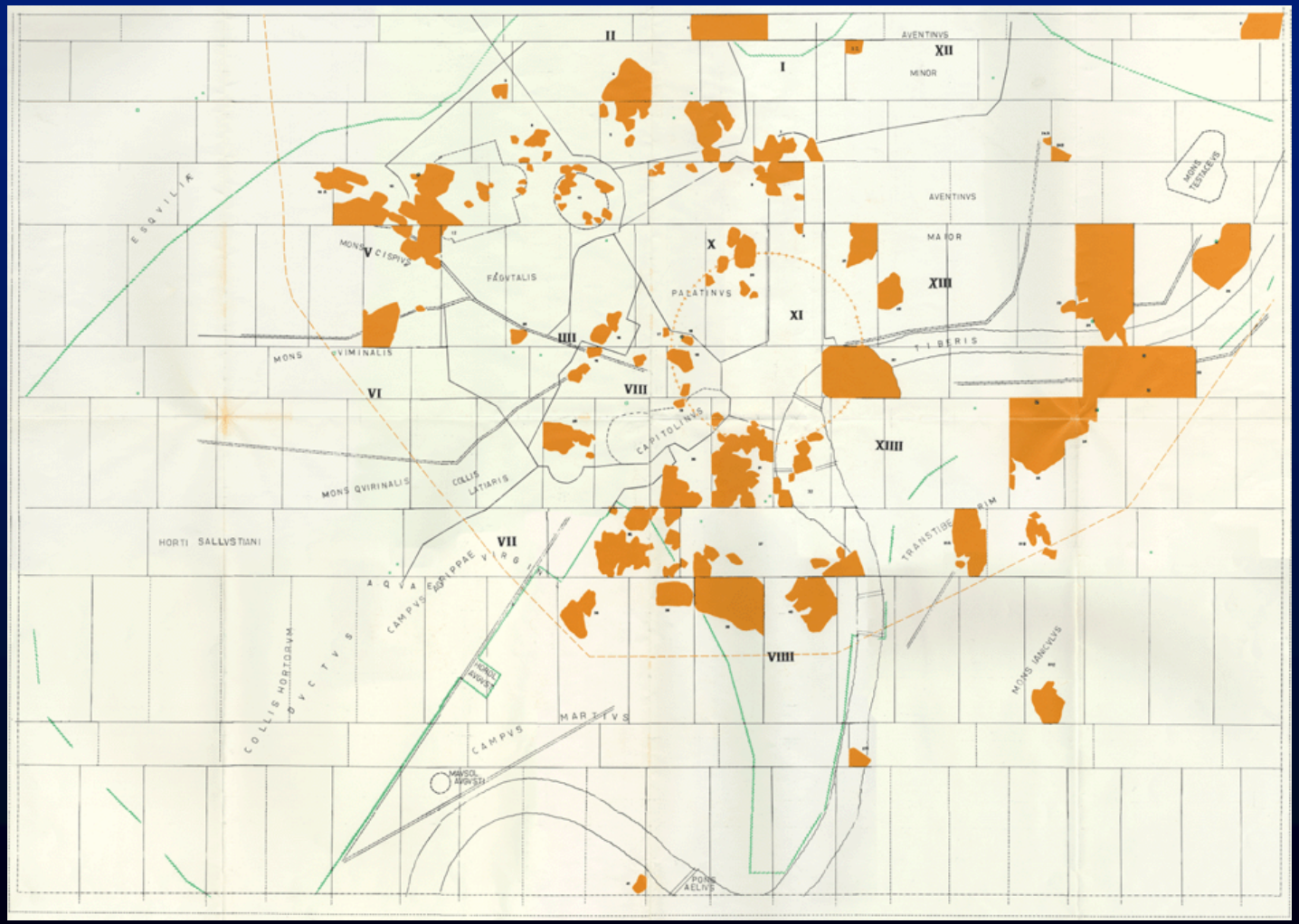


high-res server-side rendering



- high-res model stored only on server at Stanford
- client program allows manipulation of low-res model, queries server for rendered image on “mouse up” event
- one server can handle 10 queries per second = 50 users
- 10,000 downloads of client program in last 24 months

The puzzle as it now stands



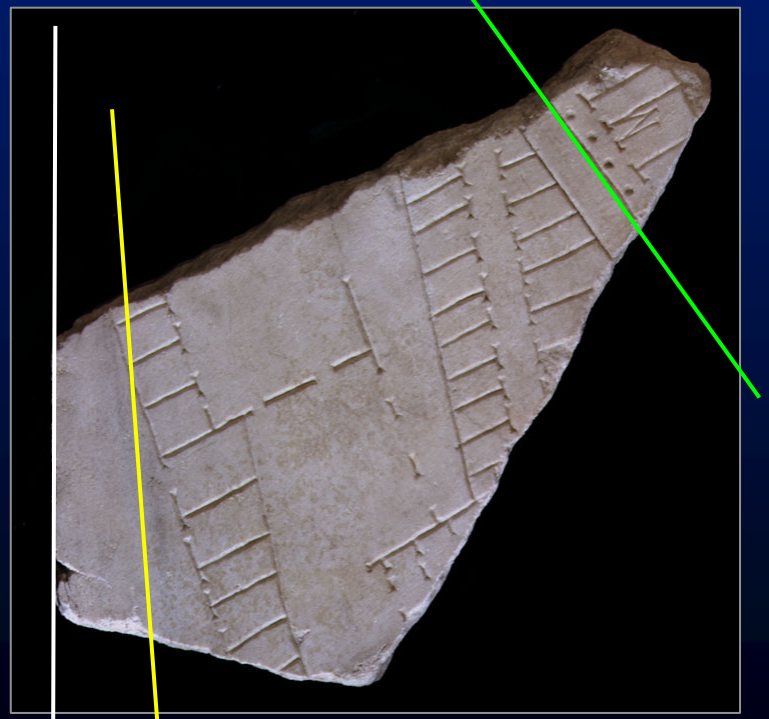
Clues for solving the puzzle

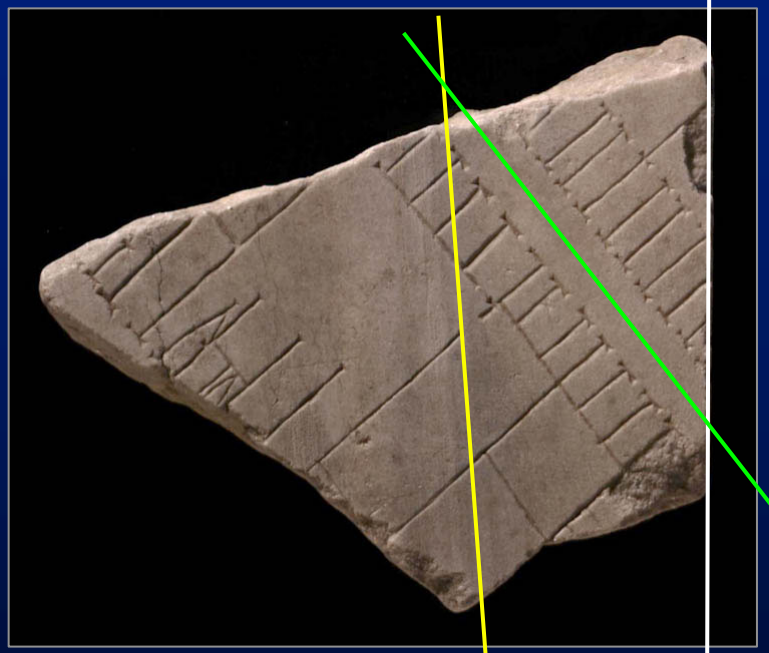
- incised lines
- incision characteristics
- marble veining
- fragment thickness
- shapes of fractured surfaces
- rough / smooth bottom surface
- straight sides, indicating slab boundaries
- location and shapes of clamp holes
- the wall: slab layout, clamp holes, stucco
- archaeological evidence

Algorithms for solving the puzzle

- fragment-to-fragment clustering

Fragments fn8 & 281





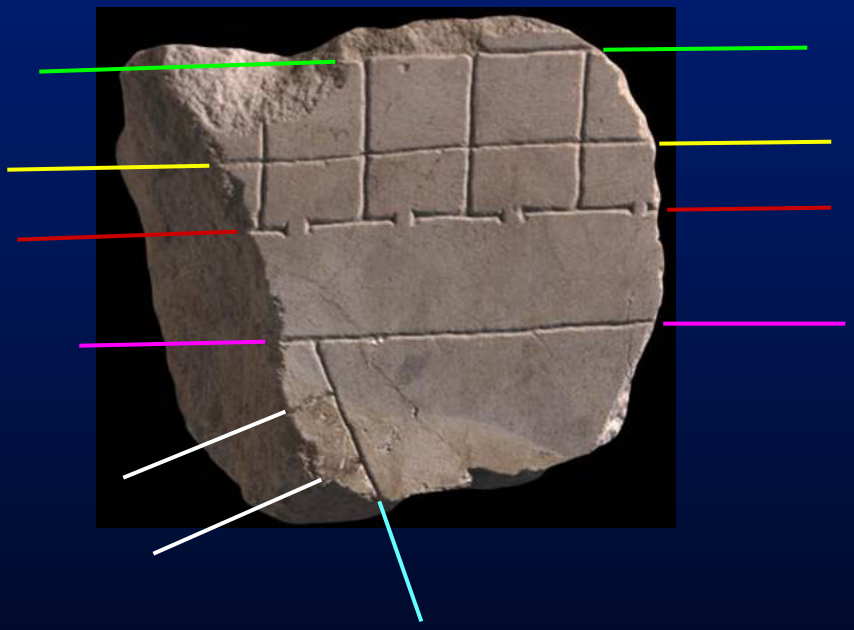
1. slab edges
2. fragment thickness
3. veining direction (relative to slab edge)
4. architectural axis (relative to slab edge)

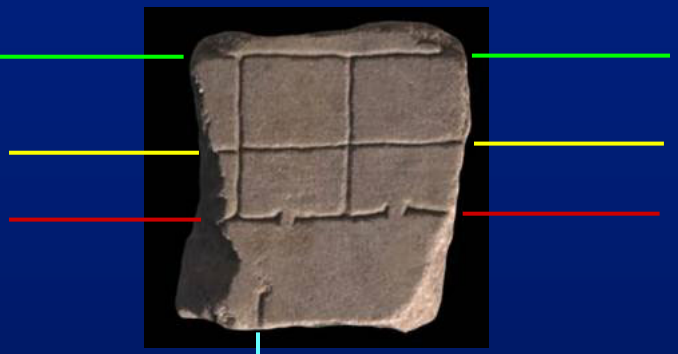
Algorithms for solving the puzzle

- fragment-to-fragment clustering
- fragment-to-fragment matching

Boundary incision matching

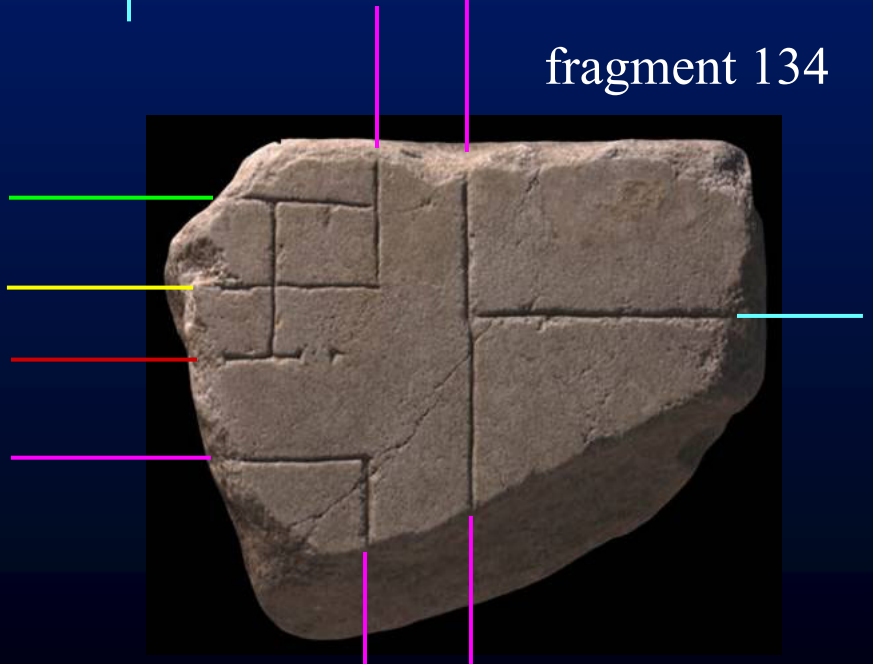
fragment 156

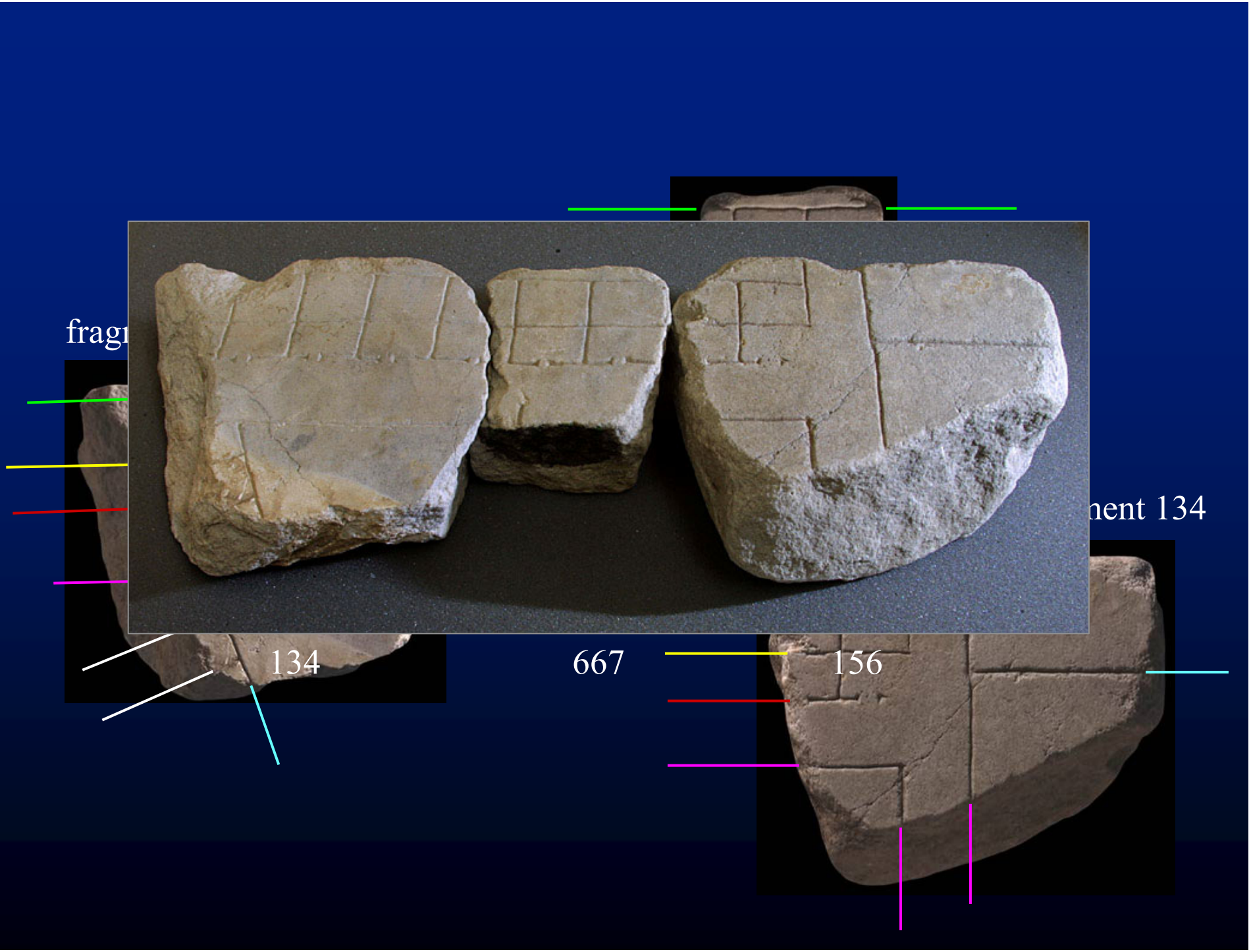




fragment 167

fragment 134

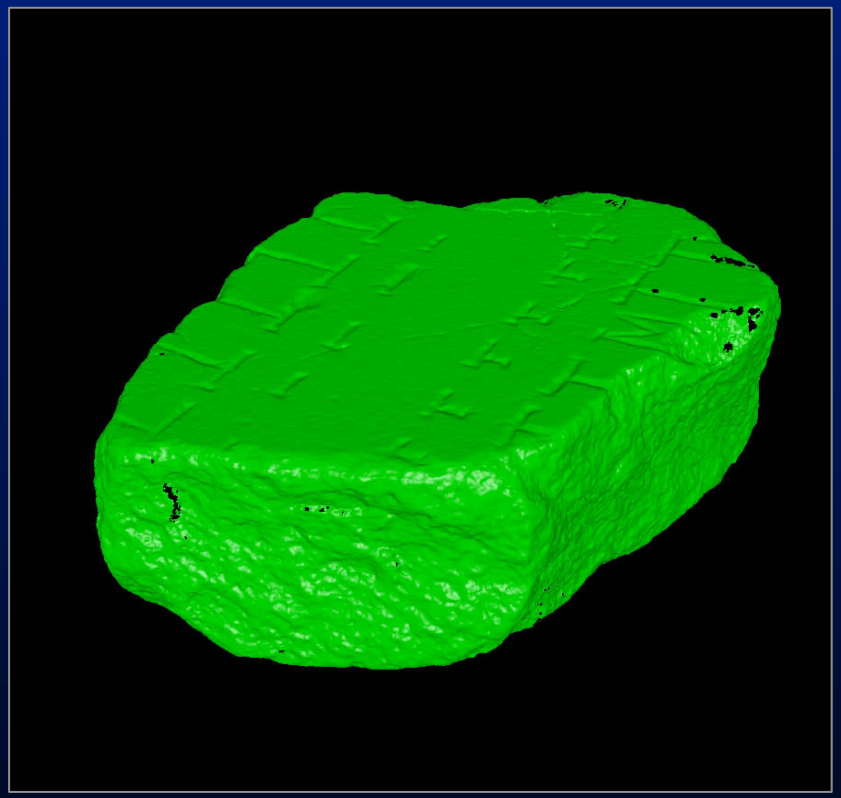



frag
134
667
156
nent 134

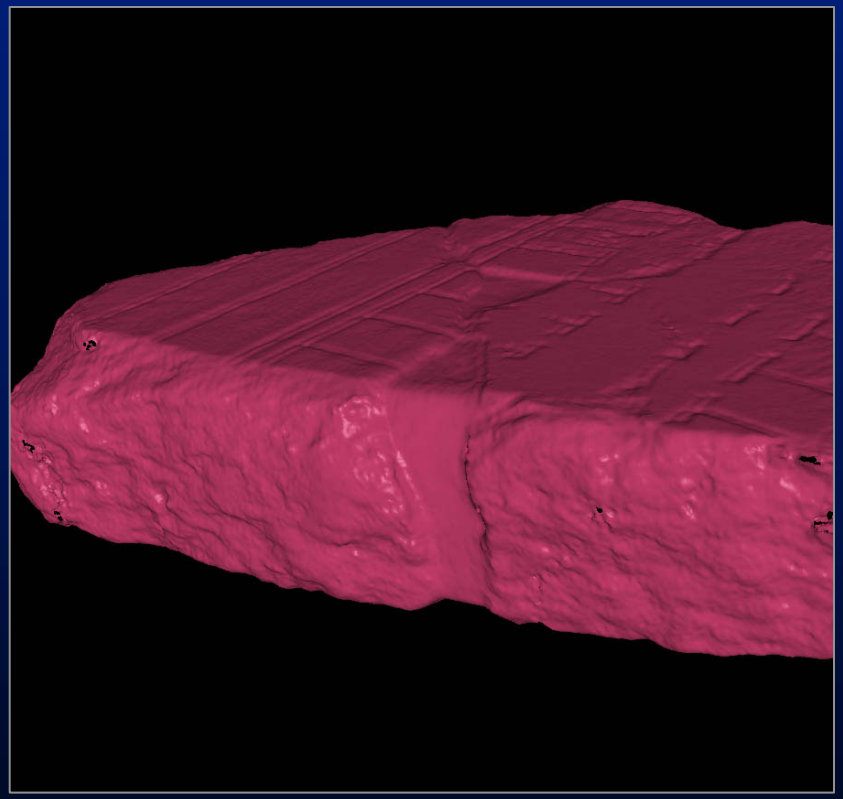
A match in the Circus Maximus

Known fragments of the Circus Maxium

We expected a “marble lock”



fragment 351

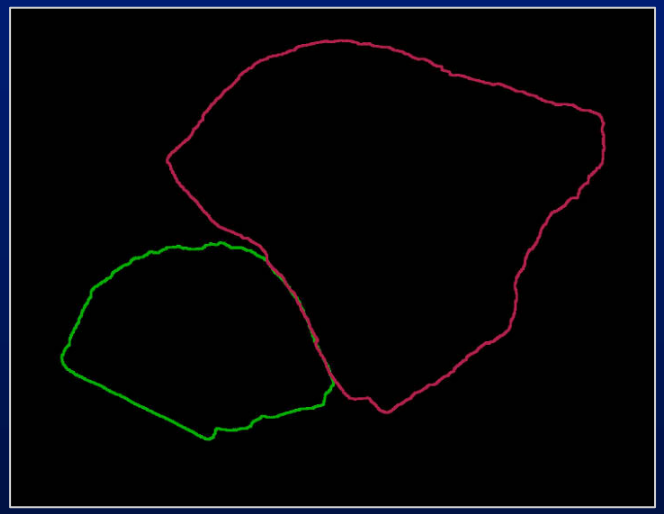


fragment fn9

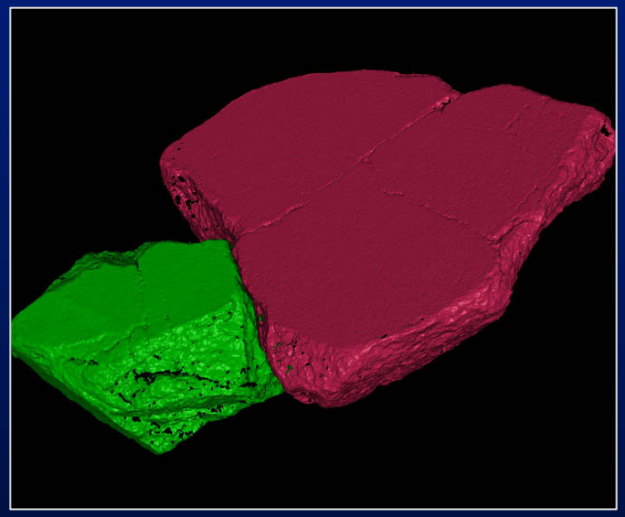
so we reopened the crates...

...and we found one!

Fracture geometry



2D fracture boundaries



3D fracture surfaces

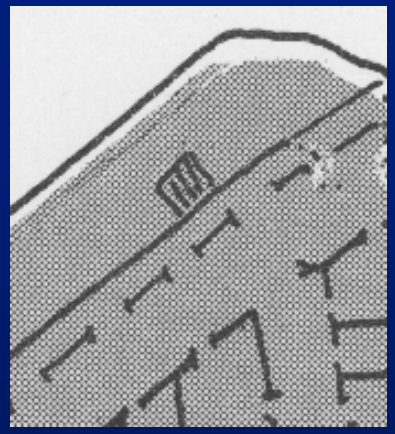
Red Sequence: L5, L7, L7, L9, L13, R2, . . .
Green Sequence: L1, L3, L8, L8, R3, R3, . . .

Algorithms for solving the puzzle

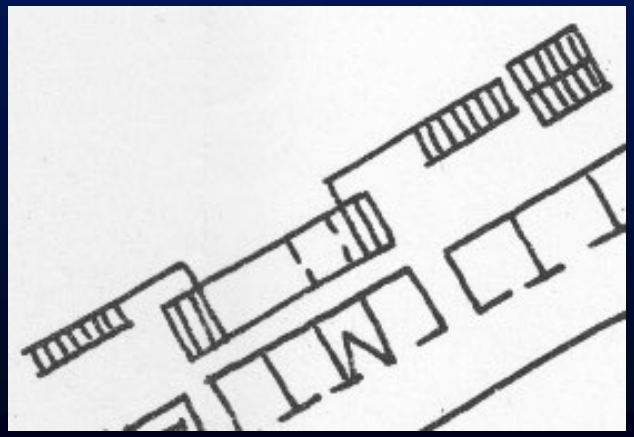
- fragment-to-fragment clustering
- fragment-to-fragment matching
- fragment-to-wall constraints

Riverfront fragments

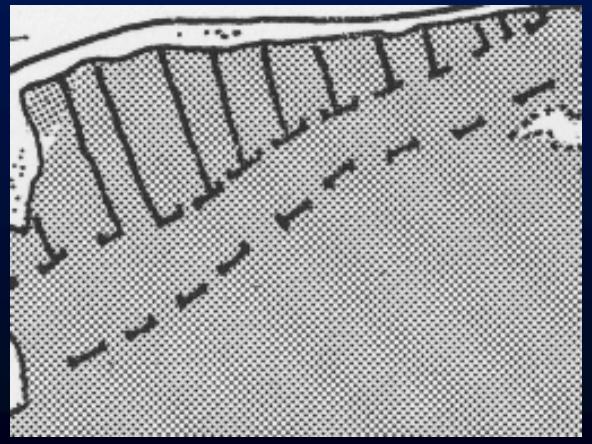
348



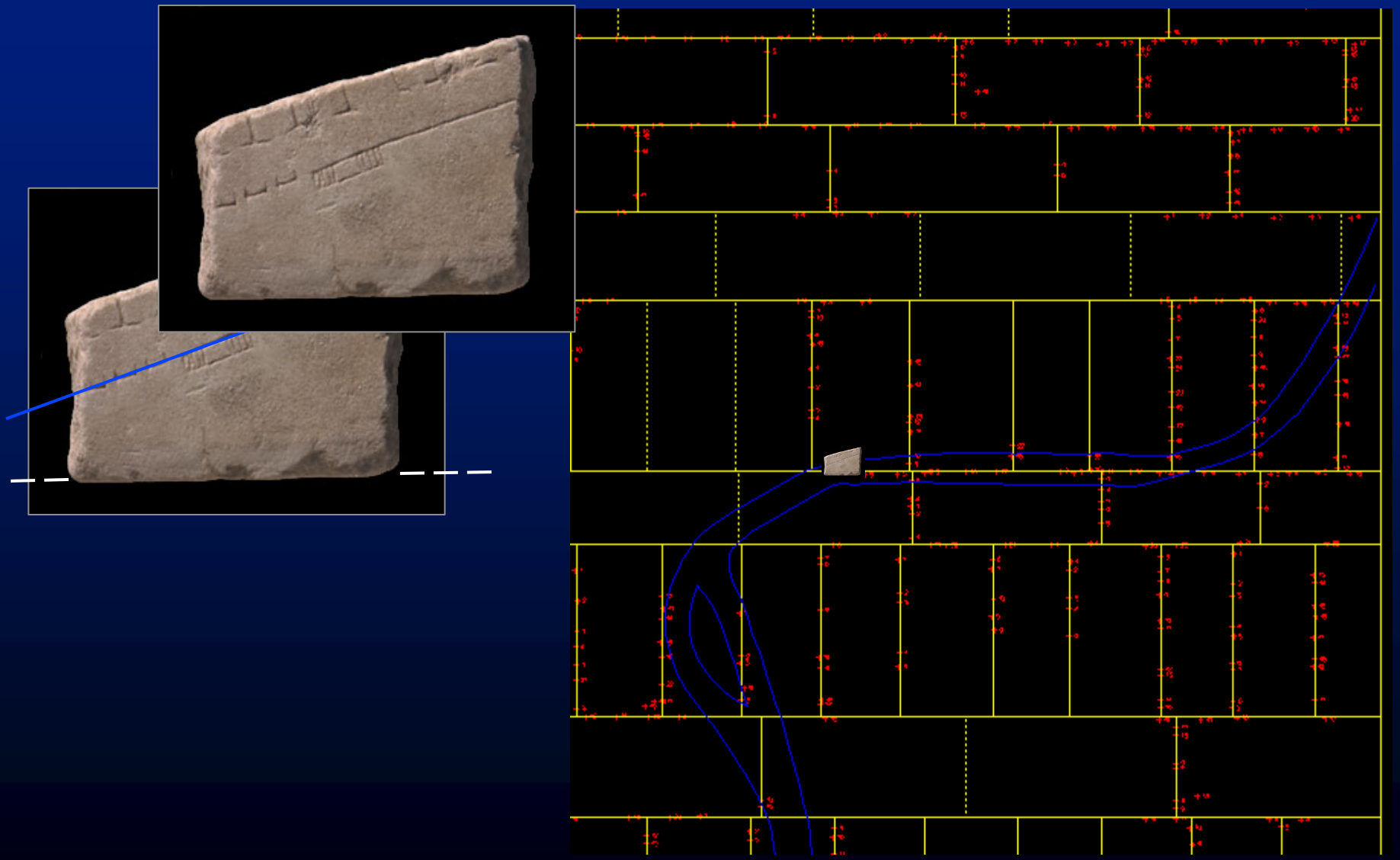
27c



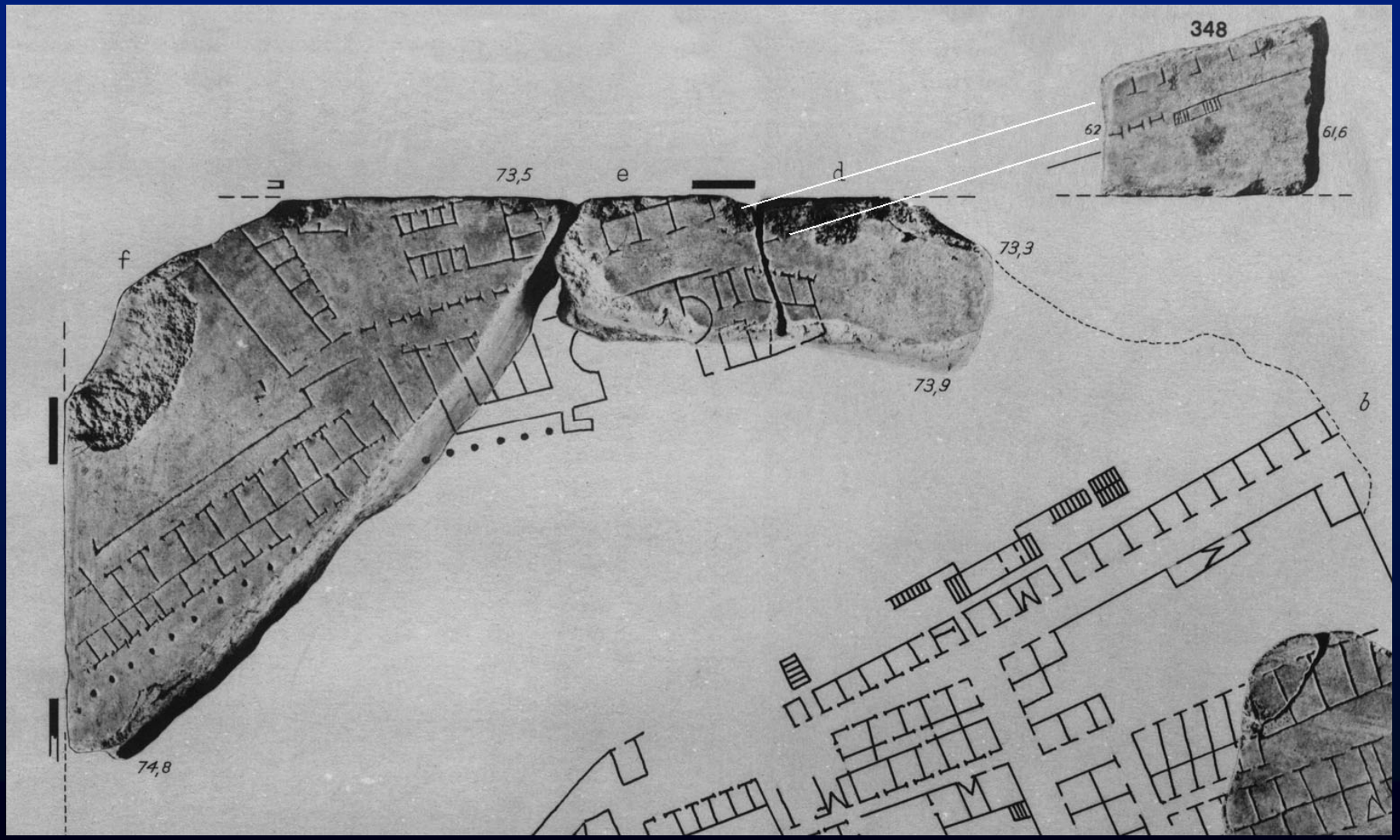
27b

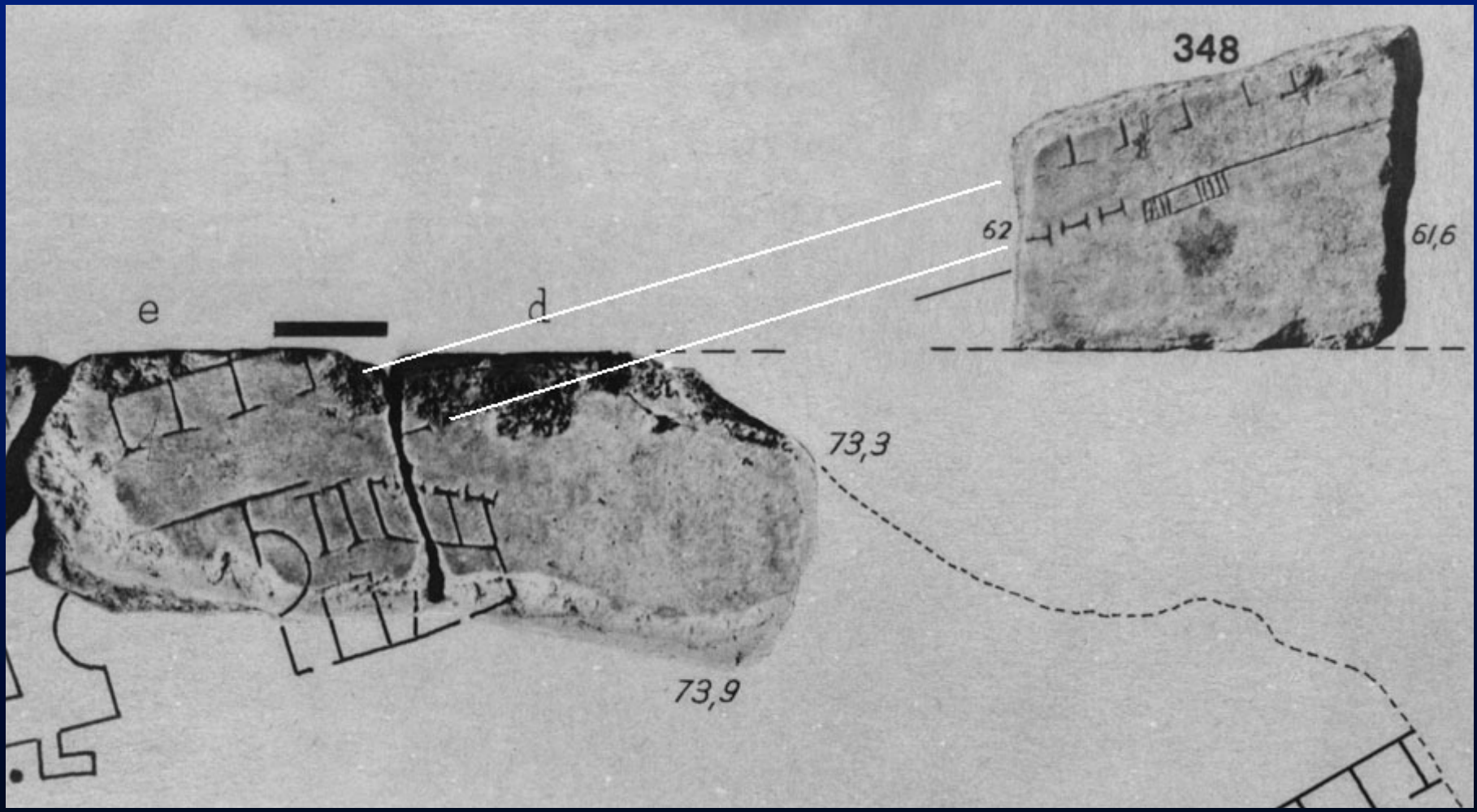


32i

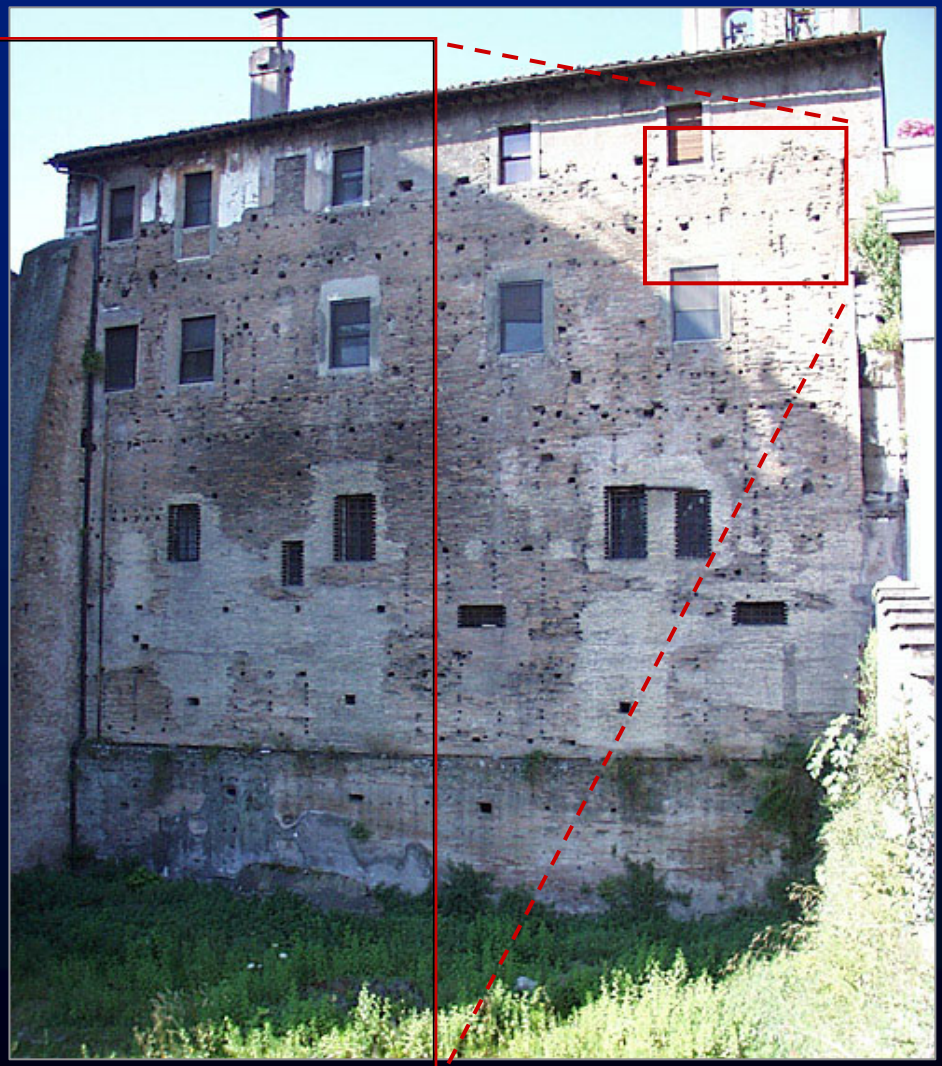


Fragment 348 in context

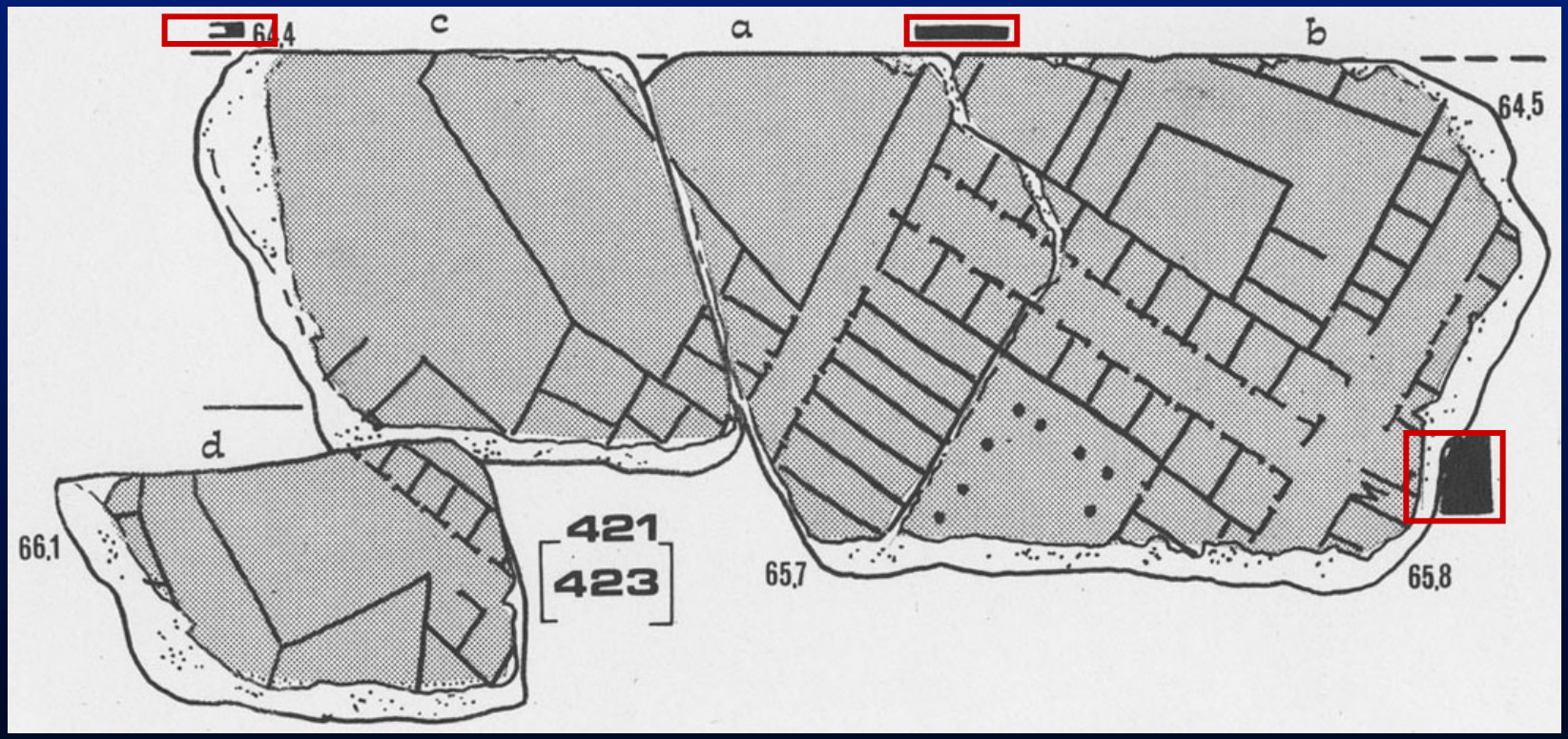


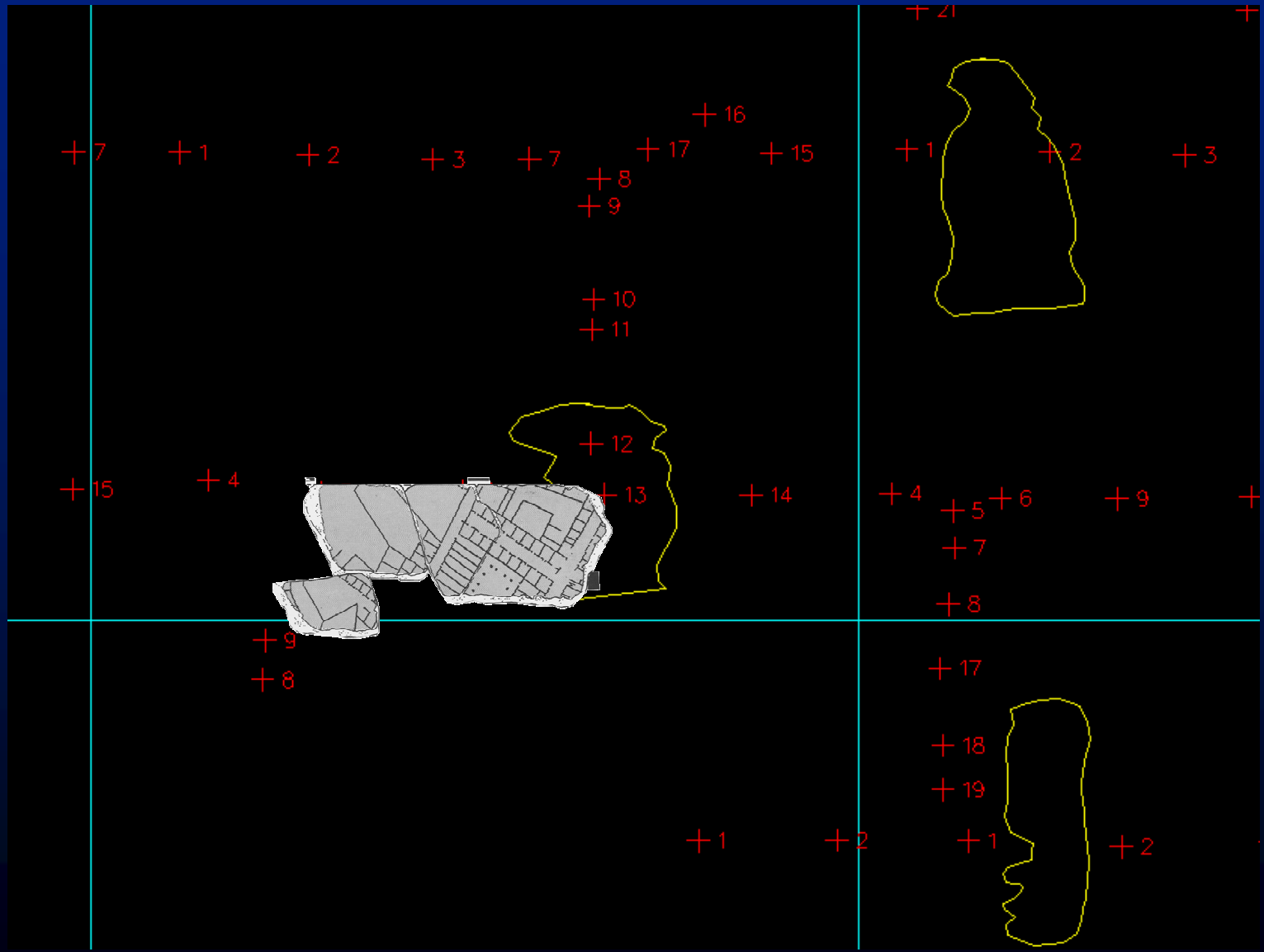


Clamp holes



Fragment 421

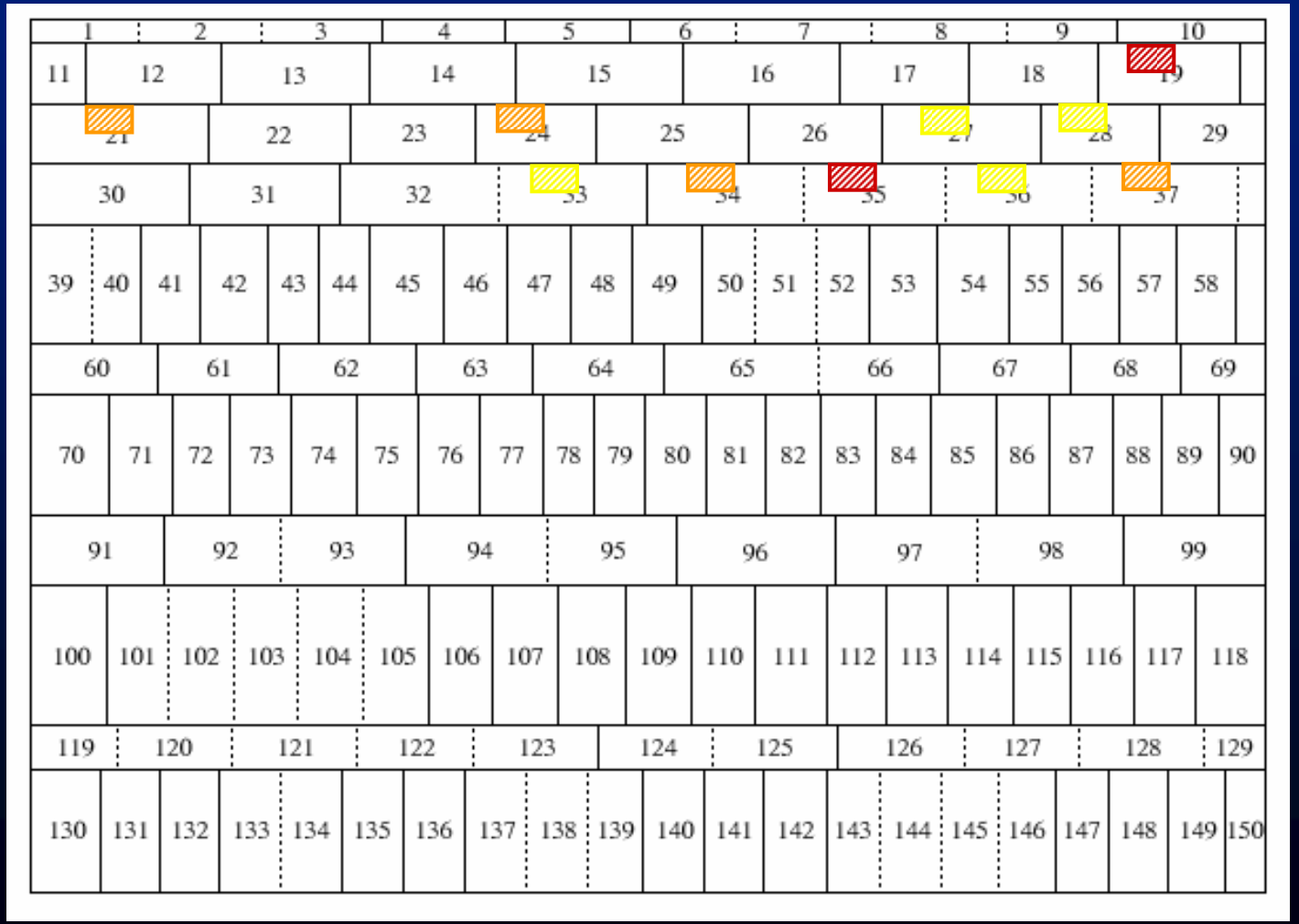



16
7
1
2
3
7
17
15
8
9
10
11
12
15
4
13
14
9
8
21
1
2
3
4
5
6
9
7
8
17
18
19
1
2
1
2

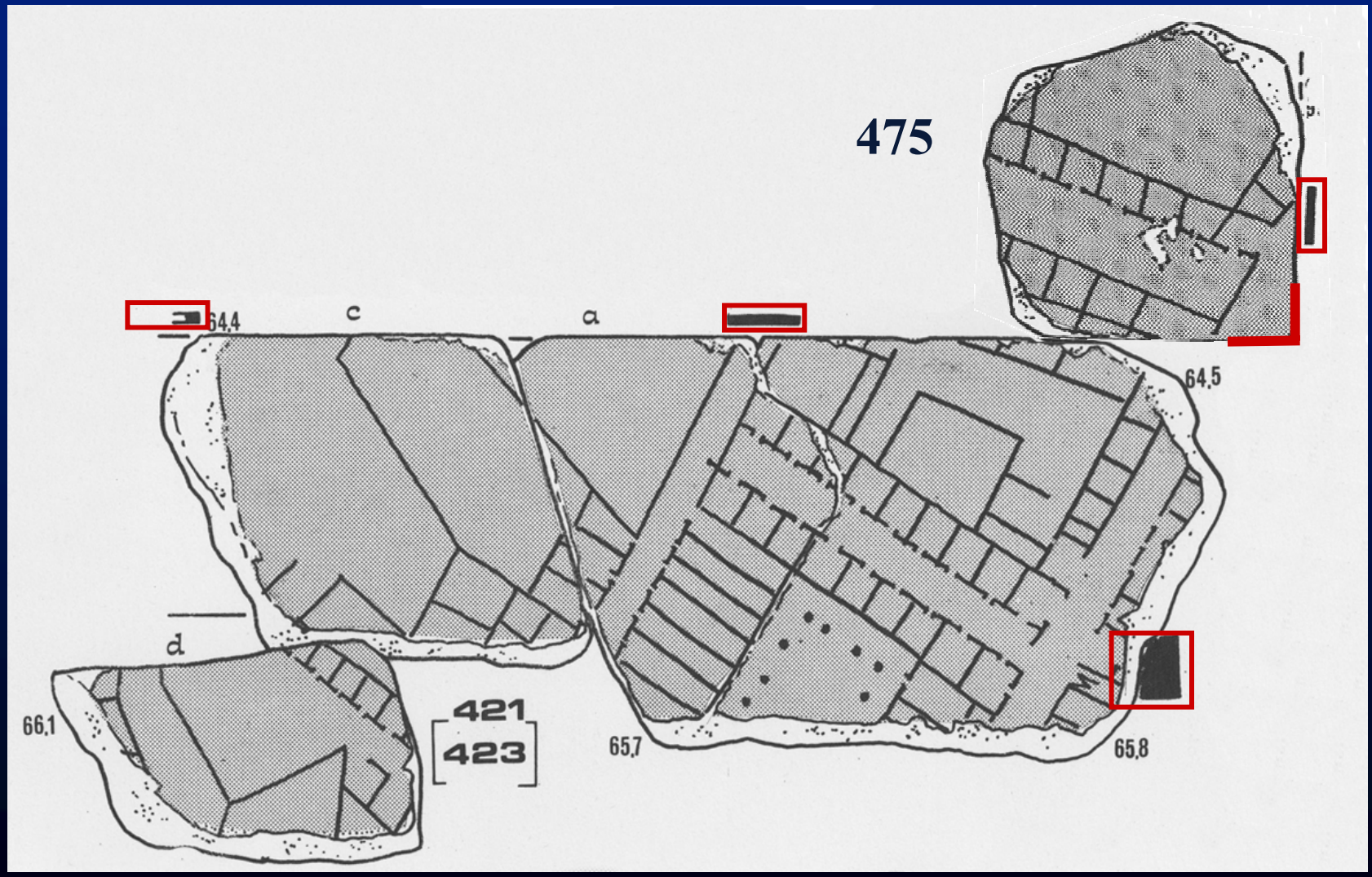
High Probability Match

Med. Probability Match

Low Probability Match



Match Fragment 421 with 475!

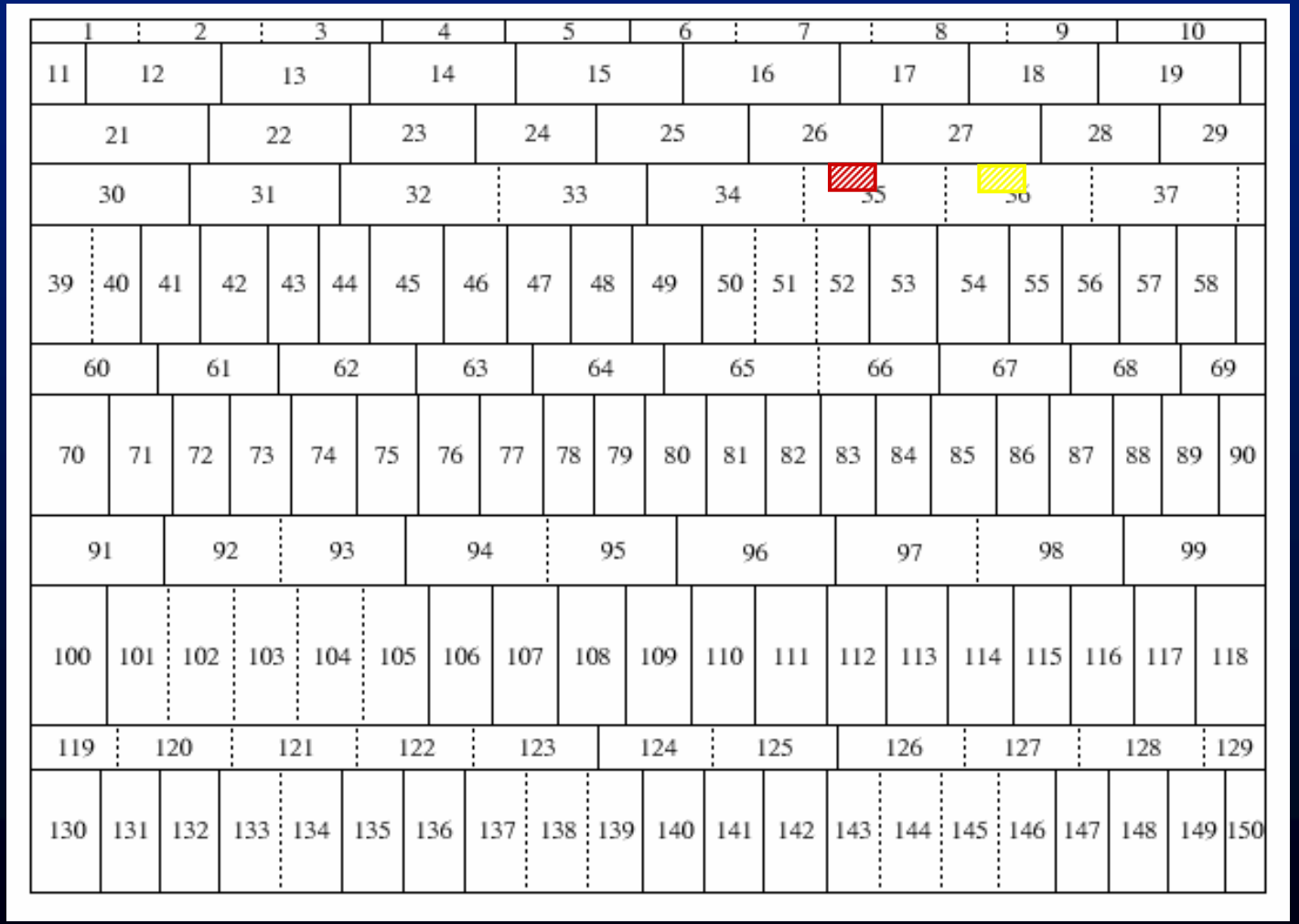


Wall Feature Matching: example results for fr. 421+475

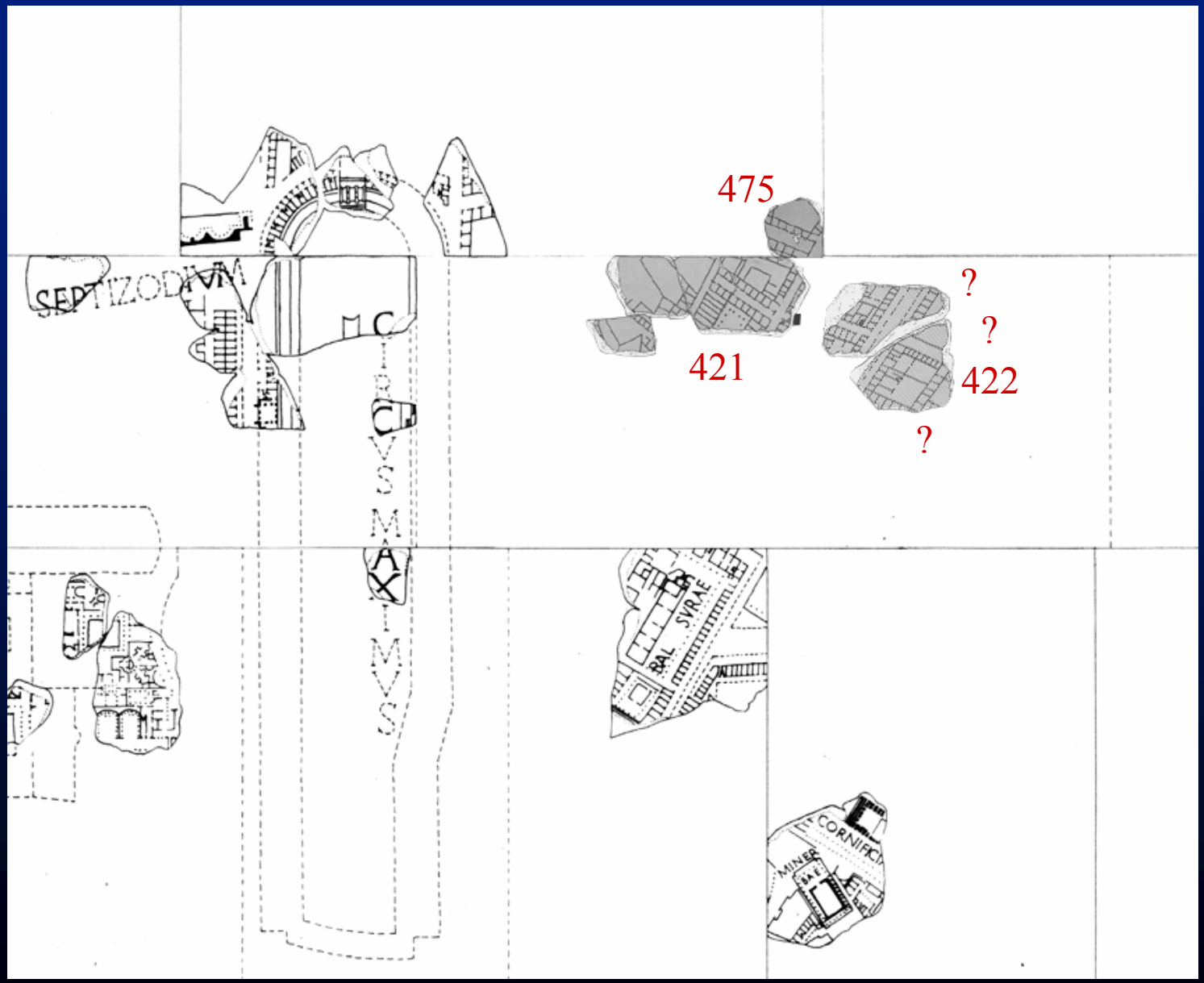
High Probability Match

Med. Probability Match

Low Probability Match



The Aventine Hill



The nature of computer-generated matches

- high probability
  - Fragments 28a, 34b, fn23 (Via Campana-Portuensis, Naumachia Augusti)
  - Fragments 156, 667
  - Fragments fn9, 351 (Circus Maximus)
  - Fragments 28a, 150 (Via Campana-Portuensis)
  - Fragments 92, 138 (Transtiberim)
  - Fragments 330, 354 (Transtiberim?)
  - Fragments 37Ail, 576 (Transtiberim)

- medium probability

Fragment 421.txt
---
clampholes a4-2:0, a4-15:1 - no, clampholes on bottom
clampholes a4-5:0, a4-3:1 - maybe
clampholes b4-1:0, b3-18:1 - no, occupied by fragment 10
clampholes b4-2:0, b4-3:1 - no, clampholes on bottom
clampholes c2-11:0, c2-9:1 -no, no tasselli on bottom
clampholes c3-17:0, c3-16:1 -no, between 2 slabs
clampholes c4-27:0, c4-18:1 - no, between 2 slabs
clampholes a7-13:0, a7-12:1 - maybe?
clampholes a8-11:0, a8-8:1 - no, tassello on bottom
clampholes a8-13:0, a8-11:1 - no, tassello on bottom
clampholes a8-16:0, a8-12:1 - no, many problems!
clampholes a9-6:0, a9-5:1 - maybe?
clampholes a10-1:0, a9-15:1 - maybe?
clampholes b6-2:0, b6-1:1 - no, occupied!
clampholes b10-1:0, b9-2:1 - maybe?
clampholes b10-2:0, b10-3:1 - no, clampholes on bottom
clampholes c9-23:0, c9-25:1 - no, between 2 slabs

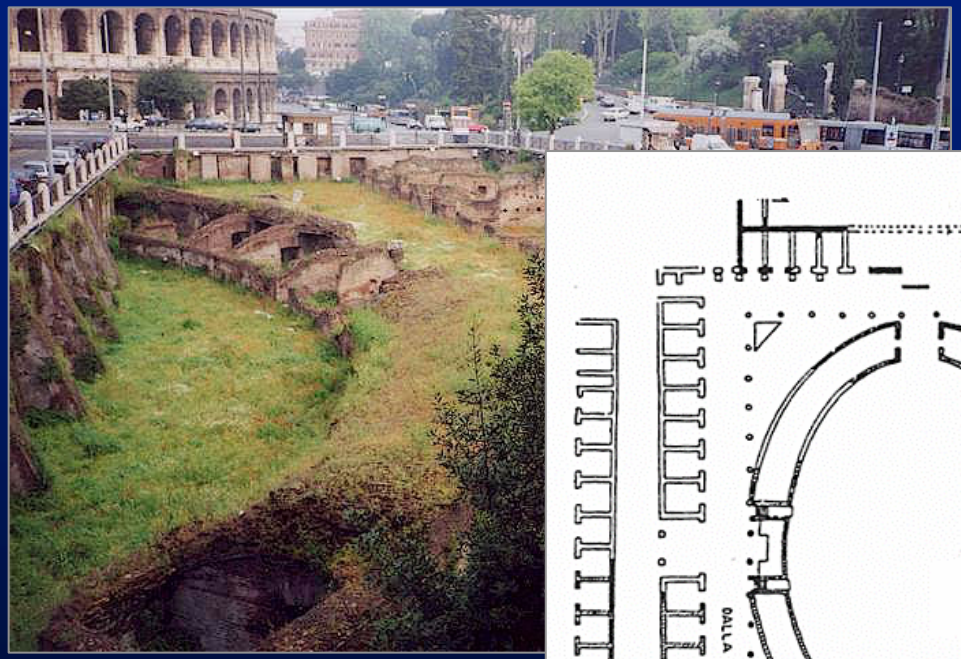
Fragment 711.txt
---
clamphole a2-1, tassello a2 (4) no, crosses slab boundary
clamphole a2-2, tassello a2 (1) no, same
clamphole a3-8, tassello a4 (3) no, same
clamphole a4-1, tassello a4 (2)
clamphole a4-2, tassello a4 (1) no, same
clamphole a4-5, tassello a4,a5 (3) no, same
clamphole a4-7, tassello a4,a5 (2)
clamphole a4-7, tassello a4,a5 (3)
clamphole a5-11, tassello a5,a6 (2)
clamphole a5-11, tassello a5,a6 (3)
clamphole b3-9, tassello b3 (2)
clamphole b3-10, tassello b3 (3)
clamphole b3-13, tassello b3 (1)
clamphole b3-15, tassello b4-1 (3)
clamphole b4-1, tassello b4-2 (2)
clamphole b4-1, tassello b4-2 (3)
clamphole b4-2, tassello b4-2 (1)
clamphole b4-6, tassello b4-1 (2)

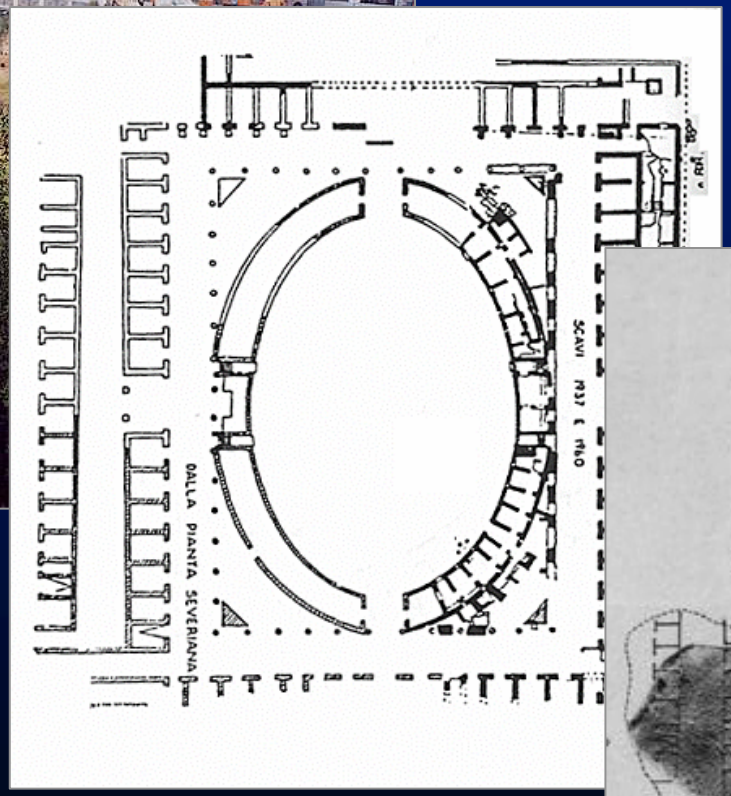
frags/102.txt MaxScore=5.5: 4,2,45
frags/103.txt MaxScore=2: 5,6,50
frags/104.txt MaxScore=1: 2,0,5
frags/105.txt MaxScore=-99999: 2,0,5
frags/106.txt MaxScore=3: 4,0,50
frags/107.txt MaxScore=-99999: 4,0,50
frags/108ab.txt MaxScore=5: 3,17,40
frags/109.txt MaxScore=-99999: 3,17,40
frags/10Aa.txt MaxScore=6.5: 3,10,50
frags/10Ab.txt MaxScore=4: 4,1,50
frags/10aa.txt MaxScore=6: 3,9,45
frags/10abcdeAaAb.txt MaxScore=8.5: 6,7,40
frags/10fgh.txt MaxScore=8.5: 0,17,30
frags/10ilmpqrs.txt MaxScore=8: 7,72,35
frags/10n.txt MaxScore=3: 3,8,40
frags/10noaa.txt MaxScore=6.5: 4,15,50
frags/10o.txt MaxScore=6.5: 3,25,45
frags/10p.txt MaxScore=5.5: 1,27,15
frags/10q.txt MaxScore=5: 3,9,50
frags/10r.txt MaxScore=3: 3,2,40
frags/10s.txt MaxScore=4: 5,5,50
frags/10tuv.txt MaxScore=6.5: 3,12,35
frags/10wxy.txt MaxScore=5: 3,2,50

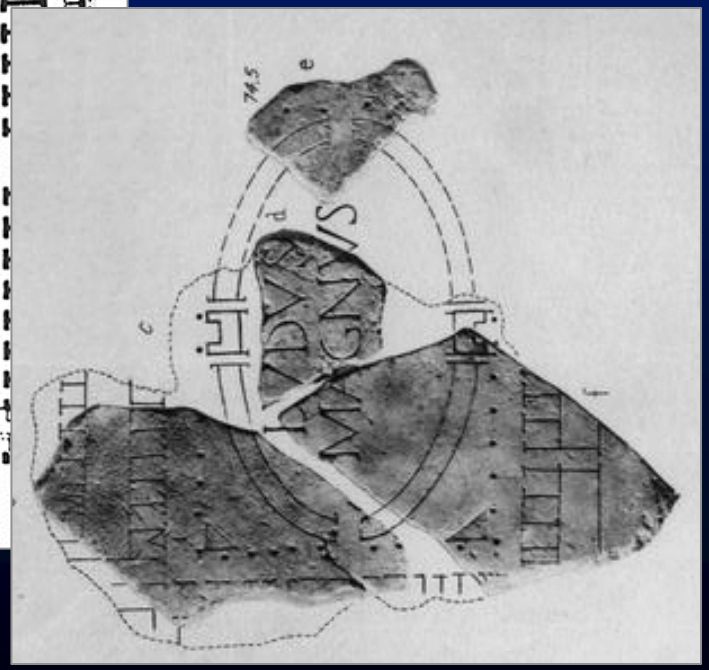
Algorithms for solving the puzzle

- fragment-to-fragment clustering
- fragment-to-fragment matching
- fragment-to-wall constraints
- fragment-to-city matching

Ludus Magnus – a gladiator training stadium







forma urbis romae

In closing...

- strawman conclusions
  - 3D scanning will become faster and cheaper, but it will never become routine

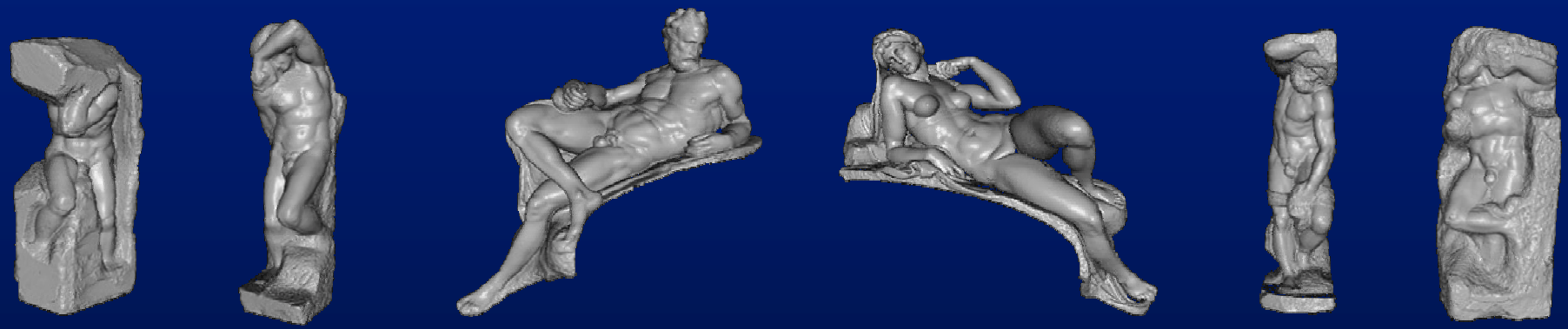
Some statues may be "unscannable" (using optical methods)

Laocoon

In closing...

- strawman conclusions
  - 3D scanning will become faster and cheaper, but it will never become routine
  - automating geometric matching is easy, but automating high-level reasoning is hard
    - » Human archaeologists are still needed!
- questions for the future
  - What is the proper role for 3D scanning?

Creating digital libraries of 3D content



- 3D archives are large
- metadata – data about data
- secure viewers for 3D models
- robust 3D digital watermarking
- viewing, measuring, extracting data
- indexing and searching 3D content
- insuring longevity for the archive

In closing...

- strawman conclusions
  - 3D scanning will become faster and cheaper, but it will never become routine
  - automating geometric matching is easy, but automating high-level reasoning is hard
    - » Human archaeologists are still needed!
- questions for the future
  - What is the proper role for 3D scanning?
  - visualization versus analysis
  - Can 3D scanning aid field archaeology?

The team in Italy
(May/June, 1999)

- Faculty
  - Prof. Marc Levoy
- Sovr. Communale
  - Prof. Eugenio La Rocca
  - Dott.ssa Laura Ferrea
  - Dott.ssa Susanna Le Pera
  - Dott.ssa Anna Somella
- Sponsors
  - Interval Research
  - Paul G. Allen Foundation for the Arts
  - Stanford University
  - Sovraintendenza Communale
  - Mellon Foundation
  - Pierluigi Zappacosta
- Staff
  - Dr. Kari Pulli
- Computer Science students
  - Sean Anderson
  - Dave Koller
  - Lucas Pereira
  - Szymon Rusinkiewicz
- Additional software development
  - Matt Ginzton
  - James Davis
  - Prof. Brian Curless (UW)

The team at Stanford
(2001-2004)

- Faculty
  - Prof. Marc Levoy
  - Prof. Jennifer Trimble
- Classics students
  - Margaret Butler
  - Elizabeth Clevenger
  - Jacob Denmark
  - John Mandsager
  - Andrew Martin
  - Marden Nichols
  - Matthew Shulman
  - Lilla Toal

Sponsors
- National Science Foundation
- Stanford University
- United Parcel Service

- Staff
  - Dr. Tina Najbjerg
  - Dr. Steve Marschner
- Computer Science students
  - Sha Sha Chu
  - Natasha Gelfand
  - Leslie Ikemoto
  - David Koller
  - Tricia Lee
  - Francois-Marie Lefevere
  - Austen McDonald
  - Rene Patnode
  - Nicolas Scapel
- Additional collaborators
  - Dott.ssa Claudia Cecamore

http://graphics.stanford.edu/projects/mich/
http://graphics.stanford.edu/projects/forma-urbis