G. APPENDIX C

Tap Test Imaging of the AA587 A300-600 Rudder

Second Examination, NASA-LaRC, Langley, VA

A Report Submitted to Matt Fox (NTSB)

by

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May 2001

This report presents the second phase of an examination of the Airbus A300-600 vertical stabilizer and rudder from the American Airlines flight 587 crash in November, 2001. A portion of the information contained in this report has been previously analyzed and submitted to Brian Murphy (NTSB) and Dave Swartz (FAA) in a report dated Dec. 7, 2001.

The following italicized sections have been cut directly from the previous report noted above as a reference for those unfamiliar with the initial work. Note that the images from the initial report are not reproduced here separately, but are combined with the latest results from NASA-Langley and presented in the accompanying figures.

INTRODUCTION

On November 28 and 29, 2001, the authors took part in the examination of an Airbus A-300-600 vertical stabilizer (tail) and rudder from the American Airlines flight 587 crash. The authors used a Computer Aided Tap Test (CATT) instrument to nondestructively characterize and acquire data from the rudder and tail. Because tap test is suited for inspecting honeycomb sandwich structures, practically all the scans were made on the rudder. This report contains images produced from the data collected and photographs of the actual parts, and presents them in a manner so as to show the areas examined. Note that because of time restraints the entire surface of the parts has not been examined; priorities were given to examination of particular areas of the rudder and tail. Included in this report is a description of the equipment used in the tap test examination, a simple explanation of the physics of the tap test, the processing of data to produce "C-scan" type images, and a method for interpreting the images. The tap test data collected on the rudder and the scan images produced should be correlated to other NDI data, including thermography data from Wayne State and Woodpecker and MIA data from Sandia, in the investigation of the vertical stabilizer failure on the AA587 A300-600.

TAP TEST EQUIPMENT

Two Computer Aided Tap Tester (CATT) units were used for the examination of the A300-600 rudder. The CATT is essentially an instrumented version of tap tests routinely performed by aircraft mechanics and inspectors. In a manual, hearing-based tap test, an impactor is struck on the surface of a composite part and the pitch of the sound generated from the impact is used as an indicator of the quality or condition of the part. Typically, a dull, lower pitched sound indicates a disbond or delamination. Inspectors will typically use an impactor and a grease pencil to mark the boundary of "bad" areas. The pitch of the sound produced is related to the local stiffness of the part. In a typical tap, the impactor stays in contact with the part surface through one half cycle of the oscillation. The higher the local stiffness, the shorter the contact time between the impactor and the surface. For a disbonded or delaminated region, the local stiffness will be much reduced and, as a result, the contact time is greatly lengthened.

The CATT uses an accelerometer to measure the contact time of a tap. A simple microprocessor uses trigger and timing circuit to measure this contact time, typically in *the range of 300-1500 microseconds for CFRP sandwiches. The circuit then passes the time value to a personal computer through a serial interface, where the data are recorded and displayed as a visual image. To encode the tap position, the CATT makes use of a thin mylar sheet with an imprinted grid, which is laid upon the part surface. With the computer assuming a specific (but user definable) tap sequence, typically a raster-type sequence, one tap in each grid square is input into a corresponding cell in a spread sheet program (MS Excel ®). This simple assumed encoding scheme allows an image of the tap duration (contact time) to be produced. If the mass of the tapper is also known, the local stiffness, in engineering units of Newtons per meter , can be calculated, enabling the production of a local stiffness image of the part surface. For this work, only the impact duration images have been produced.*

In a manual tap test, the force of impact and the angle and aim cannot be maintained in a highly reproducible manner. It is also very tedious to tap a large area by hand. For this reason the CATT system developed at Iowa State University makes use of a magnetic cart in which the repulsive force between strong permanent magnets propels the accelerometer repeatedly onto the part surface with a constant pitch and uniform impact force. The cart also speeds up the data acquisition considerably. In the AA587 rudder inspection, we used a tap spacing of ¾" and was able to scan a 6 square feet area in less than 10 minutes.

SCAN IMAGES

The images produced by the CATT scanner are similar to C-scans produced in ultrasonic scanning methods, where each point in the image corresponds to a datum taken at a particular (x,y) location in the scan region. The color of the point represents the measure impact duration (i.e., contact time) of the tap at that location. To display the contact time data collected on the AA587 rudder, a single color pallet and range was used for all the images (except the single scan on the rudder spar). The color pallet and range for the contact time (in microseconds) is shown beside the first image. The range used to display the contact time data was from 200 μs to 1200 μs, in 10 different colors. Values greater than 1200 μs would appear as black in the images.

A tap spacing of ¾" was used for all CATT scans on the rudder except the 7 scans made over the large blue letter "A" on the left rudder skin. For these 7 scans, a pitch of ½" was used. In the collage of scan images, the difference in pitch was normalized and taken into account.

INTERPRETATION OF CATT SCAN IMAGES

In interpreting the images, the general rule is that a higher value for the contact time indicates a lower stiffness, which is typical of damage. Lower contact times indicate higher stiffness. However, the contact stiffness, and hence impact duration, depends on a number of parameters including facesheet material and thickness, core material and density, presence of potting, or ply overlap and dropoff. For this reason, changes in the local image color indicate changes in the local stiffness of the surface of the part, but do *not necessarily indicate damages. Visible in the CATT scan images of various parts of the rudder are regions were the core material changes, areas where core sections were adhesively spliced, and potted core cells near hinge or actuator fittings or fasteners. It should also be noted that with severely broken panels such as those from the lower one third of the rudder, edge effects can affect the tap test results to some degree. Contact duration typically increases at a free, unsupported panel edge, and can mask subtle damage in the part.*

On both the right side skin panel and the left side skin panel of the rudder, there were a number of buckle failures of the rudder skin that ran along 45^o *lines. Tap test images clearly showed the disbond of the rudder skin from the core along such failures. A cursory comparison between tap test image and visual inspection showed that the width of the disbond was approximately the same as that indicated by the surface deformation of the skin. However, tap test images did reveal some regions of subtle reduction in local stiffness (i.e., increase of contact time) where no skin deformation was observed, but minute cracks in the paint were visible upon close examination.*

On the images presented here, a number of features were indicated. These features are identified by letters (see legend below) and their extents were marked with lines.

Legends for indications found in images:

- a. *Ply overlap*
- b. *Core splice (also labeled as "a" in the scans)*
- c. *Potting at edge/hinge/actuator*
- d. *Potted core at fasteners*
- e. *Buckle failure zone - intact*
- f. *Disbond/delamination*
- g. *Core change or # ply change*
- h. *Severe damage – may be related to buckle failure or breakup*
- i. *Zone of face sheet ply loss*
- j. *Far side core/face sheet damage or loss*
- k. *No data due to exposed/raised fasteners – tapping not possible*

We have made a number of marks on the rudder to indicate "low stiffness" or "higher stiffness." Low stiffness was caused most likely by disbond between skin and core, whereas a higher stiffness than the surrounding could be caused by core splices, core potting, ply overlap, and other manufacturing features.

Stiffness changes as measured by tap test on the top skin of a honeycomb sandwich can also be attributed to different damage scenarios below the top skin. One such region is the left rudder skin over the blue letter "A", where the lower skin was peeled off at places, with various amount of core attached to it.

PRESENTATION OF SCAN IMAGES

Over the period of two days, more than 40 scans were made with the two CATT systems brought to the site. Most of the scans were 6 square feet (2' x 3'). These scan images were put together as "collages" to show the condition of the left rudder skin and right rudder skin. On both surfaces of the rudder, we started between the 6th and 5th hinges and moved downward to the bottom edge of the rudder. Scans usually start at the line that divides the rudder skin panel and the curved leading edge fairing of the rudder and proceed toward the trailing edge. This line is referred here as the "part line". The lower one third of the rudder, below the three actuators at hinges #2, #3 and #4, had broken into approximately two large pieces on each side. These four large pieces (bearing the red and blue letters of the AA logo) were all scanned and their images assembled to the degree possible.

ROUND 2: NASA Langley

The second examination was conducted at the NASA-Langley Research Center from March 6-8, 2002. The intent of this work was to continue the examination of the subject rudder and scan as much of the available rudder surface (both outer and inner surface) as possible in the time allotted. As in the initial work, two CATT systems were employed to examine the structural composite materials of the rudder. The tap spacings used included ¾", ½" and ¼", depending on the area, orientation and access. In areas were different tap spacings were used in adjacent scans, the images have been sized appropriately to maintain continuity of scale when assembled into "collages". As in the first report, features are identified on the scan images that represent either structural features or damage. The features are again identified by letters and their extent is indicated with lines on the images.

The legend for indications found in images:

a. Ply overlap
b. Core splice (also labeled as "a" in the scans)
c. Potting at edge/hinge/actuator
d. Potted core at fasteners
e. Buckle failure zone - intact
f. Disbond/delamination
g. Core change or # ply change
h. Severe damage – may be related to buckle failure or breakup
i. Zone of face sheet ply loss
j. Far side core/face sheet damage or loss
k. No data due to exposed/raised fasteners – tapping not possible
l. Ground strap

Also as noted in the first report, we have made a number of marks on the rudder surfaces indicating areas of "low(er) stiffness" and "high(er) stiffness". These marks typically correspond to the marks noted on the images with lines and letters, although the reader should note that not all makes indicated on the images will be found on the rudder skin. In the rudder right side images, the reader will note that there are differences in color when comparing like areas on the inside and outside of the rudder, and when comparing the right side images to those from the left side. The particular areas are marked with a large parenthesis and asterisk. It is the belief of the authors that the accelerometer in one of the CATT system mechanized carts was in the process of failing. Upon returning from the tests, this accelerometer was tested and found to be outside of specifications. Although the images produced using this sensor appear to be "biased" toward higher colors, the sensitivity of the system was degraded little. The types of structural features and damage readily distinguishable in the images from the "good" accelerometer are still visible in those images produced using the failing accelerometer.

SCAN IMAGES

The CATT systems were used to collect over 70 scans during this second examination of the rudder. The data from these scans have been assembled into "collages" and combined with those from the previous data acquired in New York. In the first examination, only the outer surfaces of the composite panels were examined, whereas in this work data from both outer and inner surfaces has been collected. The images are assembled into left and right side, inner and outer surface groups and "pasted" over scale drawings of the rudder, so as to aid in scaling and alignment.

FIGURE CAPTIONS

The following is a list of the figures with a brief description of the content. Note that all images of the left and right sides include images from the first and second examinations of the rudder.

Figure 1 shows a pair of photos of the assembled parts of the rudder, left and right sides. (photos by M. Fox)

Figure 2 shows a collage of the rudder left side tap test images, with the inside surface scans on the top and the outside images on the bottom. A legend in the upper right corner of the figure shows the color scale and the corresponding tap duration values. This color scale is common to scan images. Note that the images are superimposed on top of a scale drawing of the rudder.

Figure 3 shows the collage from Figure 2 with markings indicating structural features and damage.

Figure 4 shows a collage of the rudder right side tap test images, with the inside surface scans on the top and the outside images on the bottom. Again, the images are superimposed on top of a scale drawing of the rudder.

Figure 5 shows the collage from Figure 4 with markings indicating structural features and damage. The asterisked regions have anomalous colors due to an out-of-spec accelerometer as explained in the text.

Figure 6 shows a collage of the rudder front spar tap test images. Only the outer surface of the spar regions was scanned and imaged.

Figure 7 shows the collage from Figure 6 with markings indicating structural features and damage.

Figure 8 shows an assembled view of all tap test images, spread symmetrically about the front spar.

OBSERVATIONS AND DISCUSSION

Based on the assembled CATT scan images, we can make the following observations and comments.

1. The photo in Fig. 1 shows the left-hand rudder skin and the right-hand rudder skin after the broken pieces from the lower one third of the rudder were reassembled. Note that the photo was taken at an angle, which distorted the aspect ratio of the rudder. The width of the rudder at the bottom is actually more than twice of that at the top.

2. The images of the inside surface and the outside surface of the rudder skin showed a high degree of consistency. For example, in Fig. 4 of the right-hand skin of the rudder, the same buckle failures (dark brown lines) appeared symmetrically in the CATT scans of both the inside surface and the outside surface throughout the length of the rudder. Thin green/blue lines indicating a higher stiffness (believed to be core splices and/or ply overlaps) also appeared symmetrically on both the inside and outside images. This consistency is particularly noticeable for the upper two thirds of the rudder that remained intact. For the badly broken pieces from the lower one third, the damages detected by CATT scans on the outside surface of the skin were often different from those on the inside surface due to the presence of often different damages on both surfaces.

For core splices, the same indication of stiffness increase should appear on both surfaces. For buckle failures of the honeycomb facesheet, as the authors recall, most of the buckled disbonds were on the outside surface of the honeycomb sandwich. Evidently these buckle failures were also detected and imaged by CATT scans on the inside surface. Unfortunately there was not sufficient time during the two rounds of tests to carefully correlate the features in the image with the condition of the inside and outside surfaces.

3. The most severe damages to the rudder occurred near hinges #2, #3 and #4, where the rudder actuator was attached. Unfortunately, the left and right skin panels near these three hinges were badly broken and rather difficult to scan. For the upper two thirds of the rudder, the most prominent damage by far was the large buckle failures near hinge #5. It is interesting to note that the propagation patterns of the facesheet failure were different for the left-hand skin and the right-hand skin. On the right-hand skin of the rudder, the buckle failure seemed to have propagated from hinge #5 at almost 90 degrees outward (toward the trailing edge), quickly forming an upward 45 degree branch and then a downward 45 degree branch after propagating one half of the width. In contrast, the

buckle failure on the left-hand skin propagated mostly in a downward 45 degree direction, although a branch also propagated upward along the leading edge spar.

4. When the scan images are used to locate and correlate with features on the part, one should keep in mind that the process of piecing together more than one hundred images is not perfect. Not all scans were made with the same "pitch" (i.e., distance between taps) so the resulting images were scaled before joining together. Another source of error was that when the data in an EXCEL spreadsheet were committed to a printer, there was usually a slight distortion of the aspect ratio. This is usually not a major problem, but has a non-negligible effect when a large number of images were joined together to form a long and narrow image. Finally, the scaled line-drawing over which the CATT scan images were superimposed does not appear to be a plane view from a perpendicular perspective, whereas all the images were taken on the surface of the skin.

5. As stated above, there were some differences in the shade of the images, especially for the right-hand skin, between the scan data acquired in New York and those obtained in NASA Langley. The difference was believed to be due to a failing accelerometer, which was found to be out of spec after the round of scans in Langley. However, the change seemed to be a constant scaling factor which did not affect the ability to image the damages and internal structures of the rudder skins.

CONCLUSIONS

Combining the 40 some scans from New York and the 75 scans from NASA Langley, we have imaged more than 400 square feet of the inside and outside surfaces of the rudder skin panels. Due to time limitation (with less than three hours available after the separation of the left and right halves), we covered only about three fourths of the inside surfaces of the large, intact section of the rudder. However, the inside surfaces of the broken pieces from the lower one third of the rudder were all scanned to the extent possible. The CATT scan images showed considerable information for both the damages incurred in the accident and the normal internal structures such as changes of the honeycomb core density and thickness, the presence of core splices, ply overlaps, and lightning/grounding straps. It is hoped that this collection of combined images can serve to document the damage conditions of the rudder and contribute to the determination of the sequence of events and the final cause of the accident.

ACKNOWLEDGMENT

We wish to thank the following people for all their assistance to our endeavor: Brian Murphy and Matt Fox of NTSB, Dave Swartz of FAA, Bill Winfree of NASA-LaRC, and Brian Larson of Iowa State. Finally we thank Lisa Brasche for providing the travel and time resources to make the effort possible.

Fig. 1

Left Side

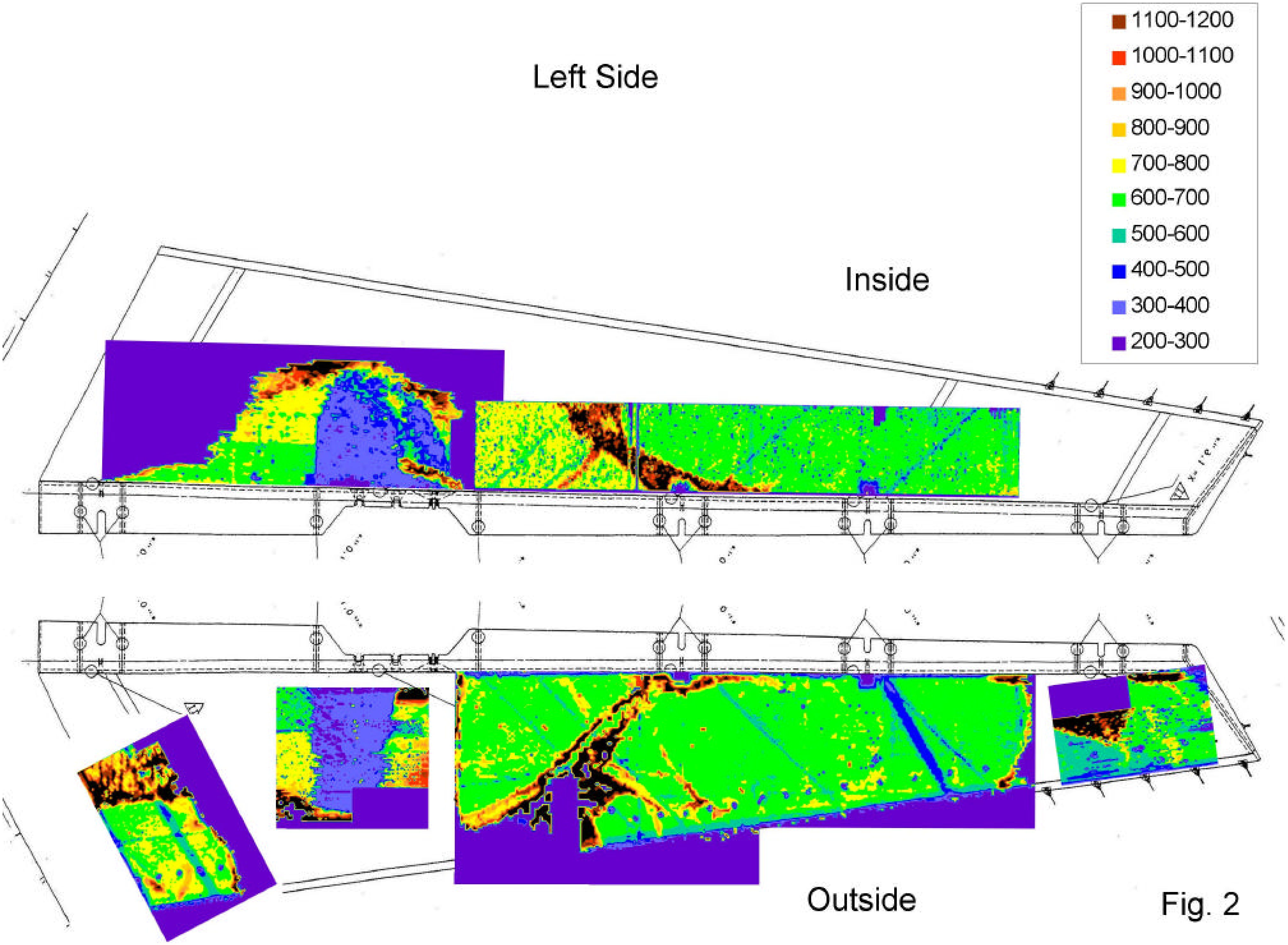


Fig. 2

Left Side

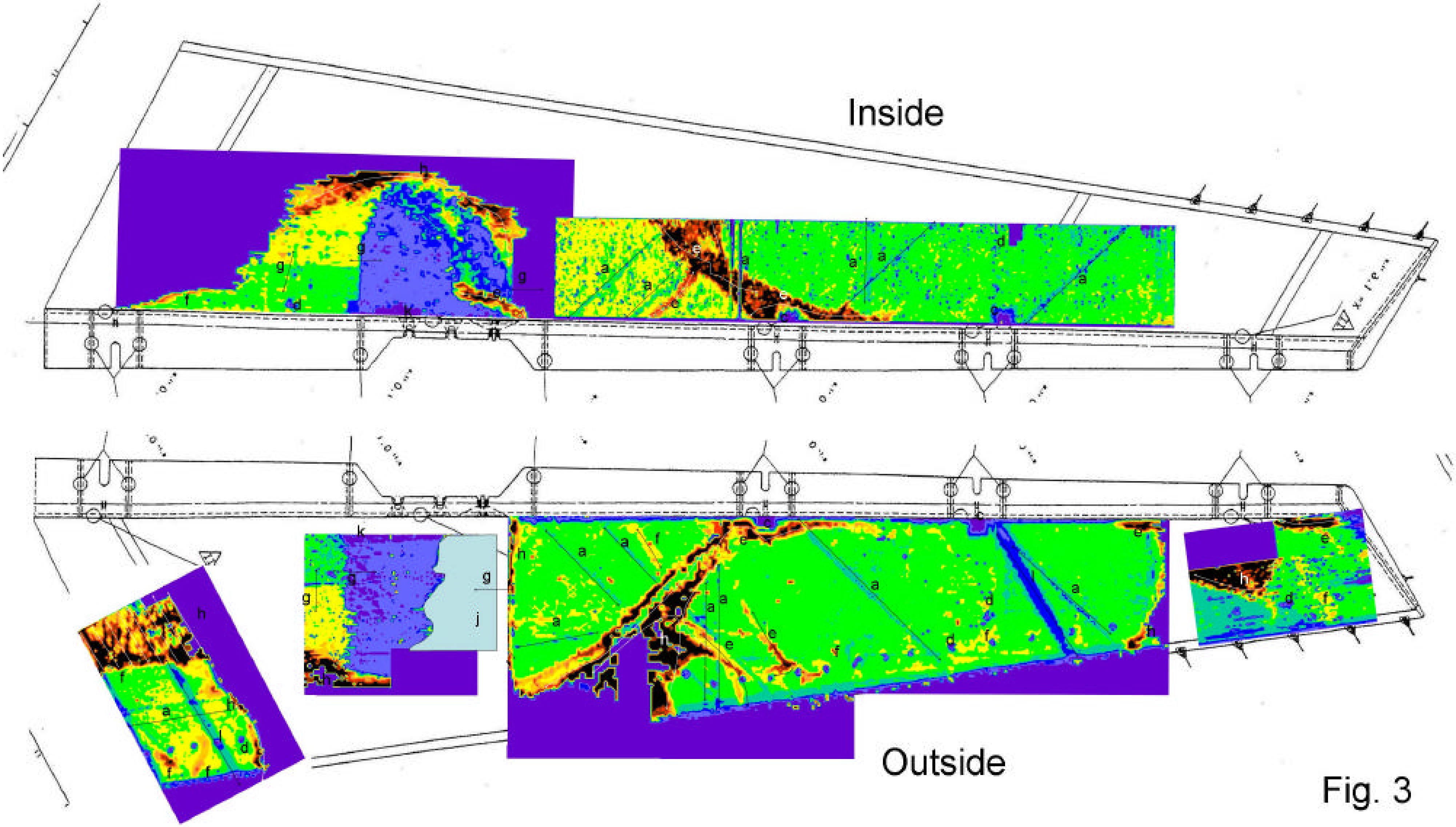


Fig. 3

Right Side

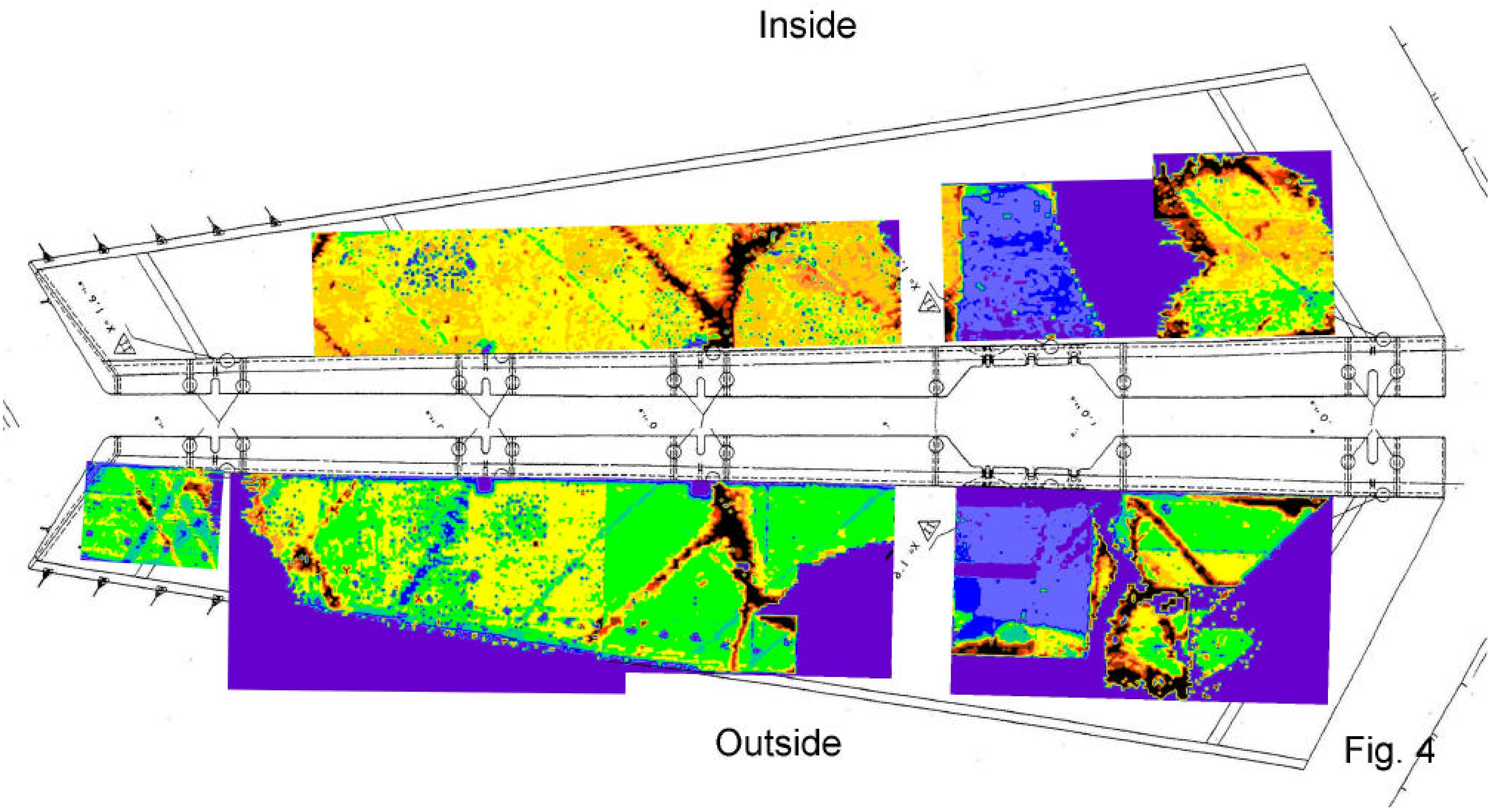


Fig. 4

Right Side

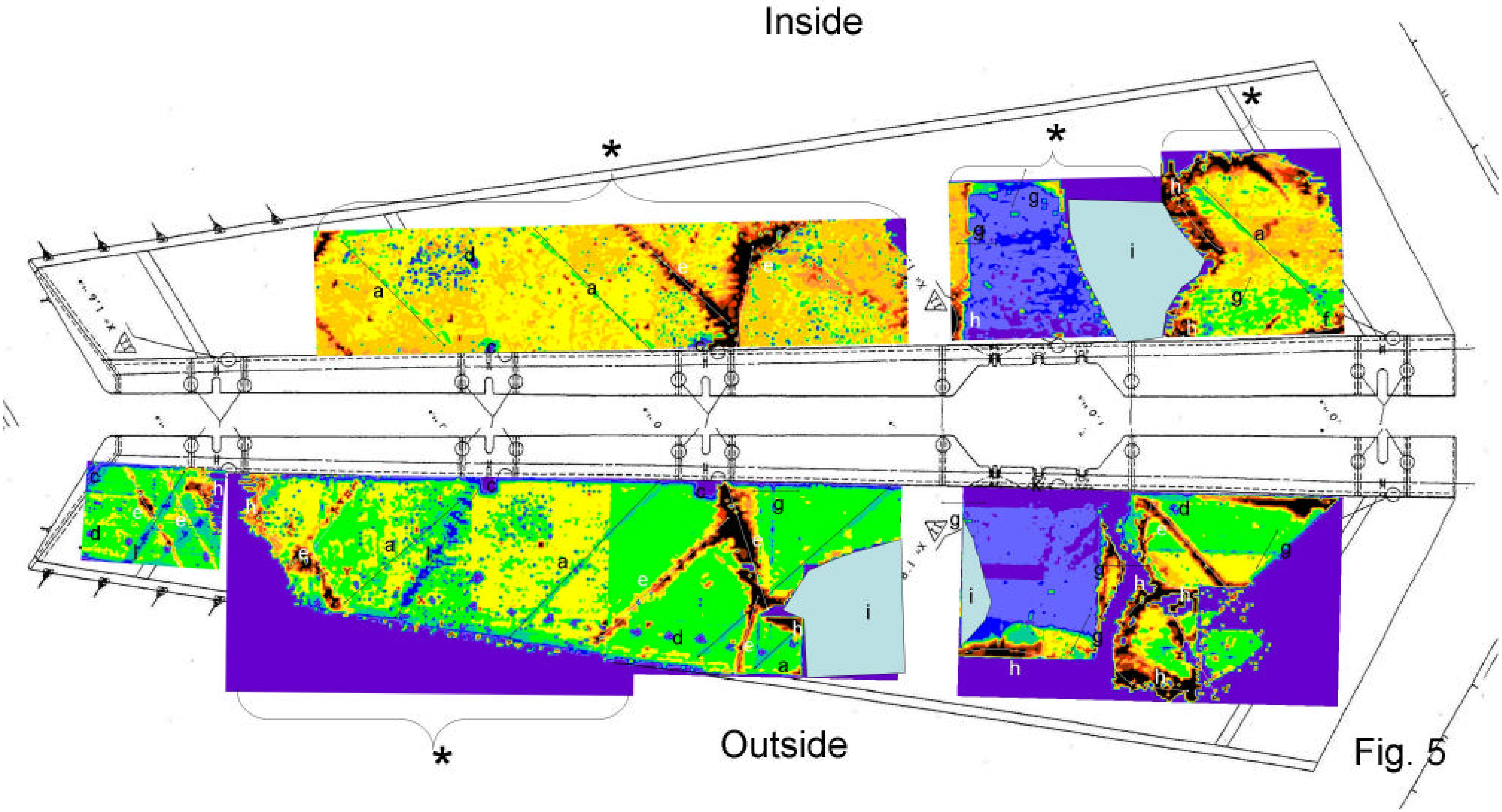
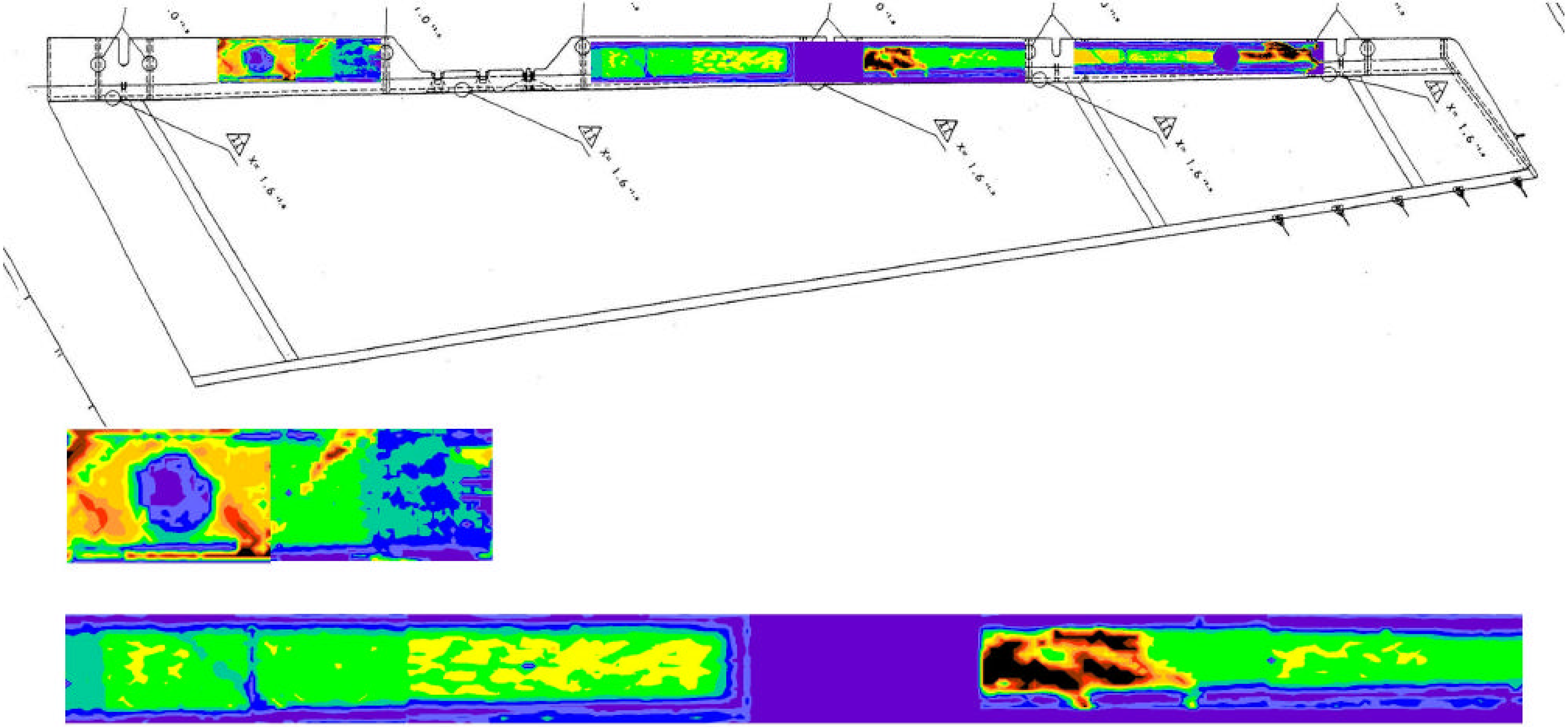


Fig. 5

Front Spar



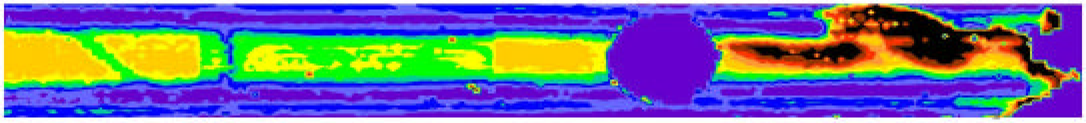


Fig. 6

Slide7.JPG (2880x2160x16M jpeg)

Front Spar

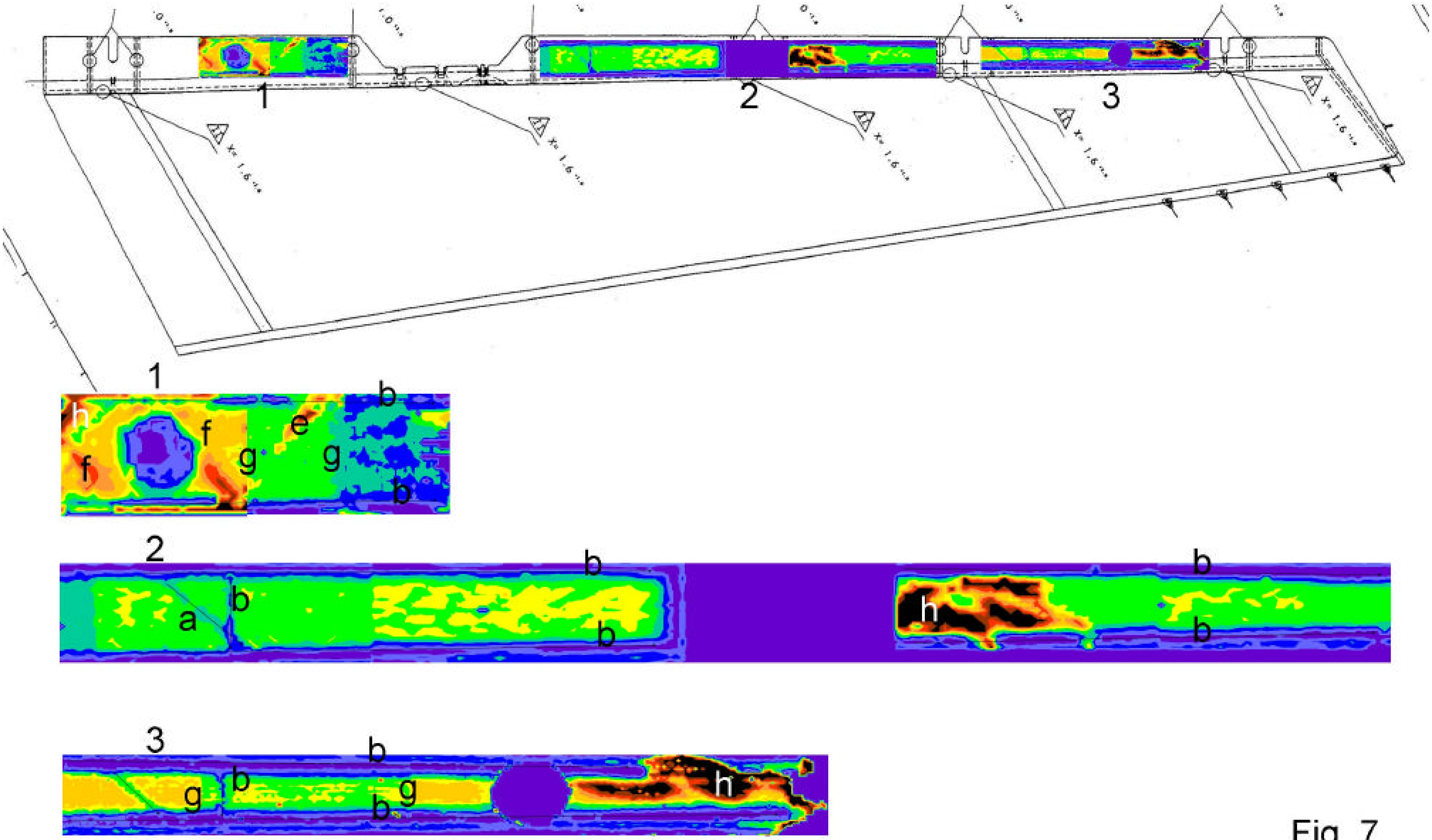


Fig. 7

Slide8.JPG (2880x2160x16M jpeg)

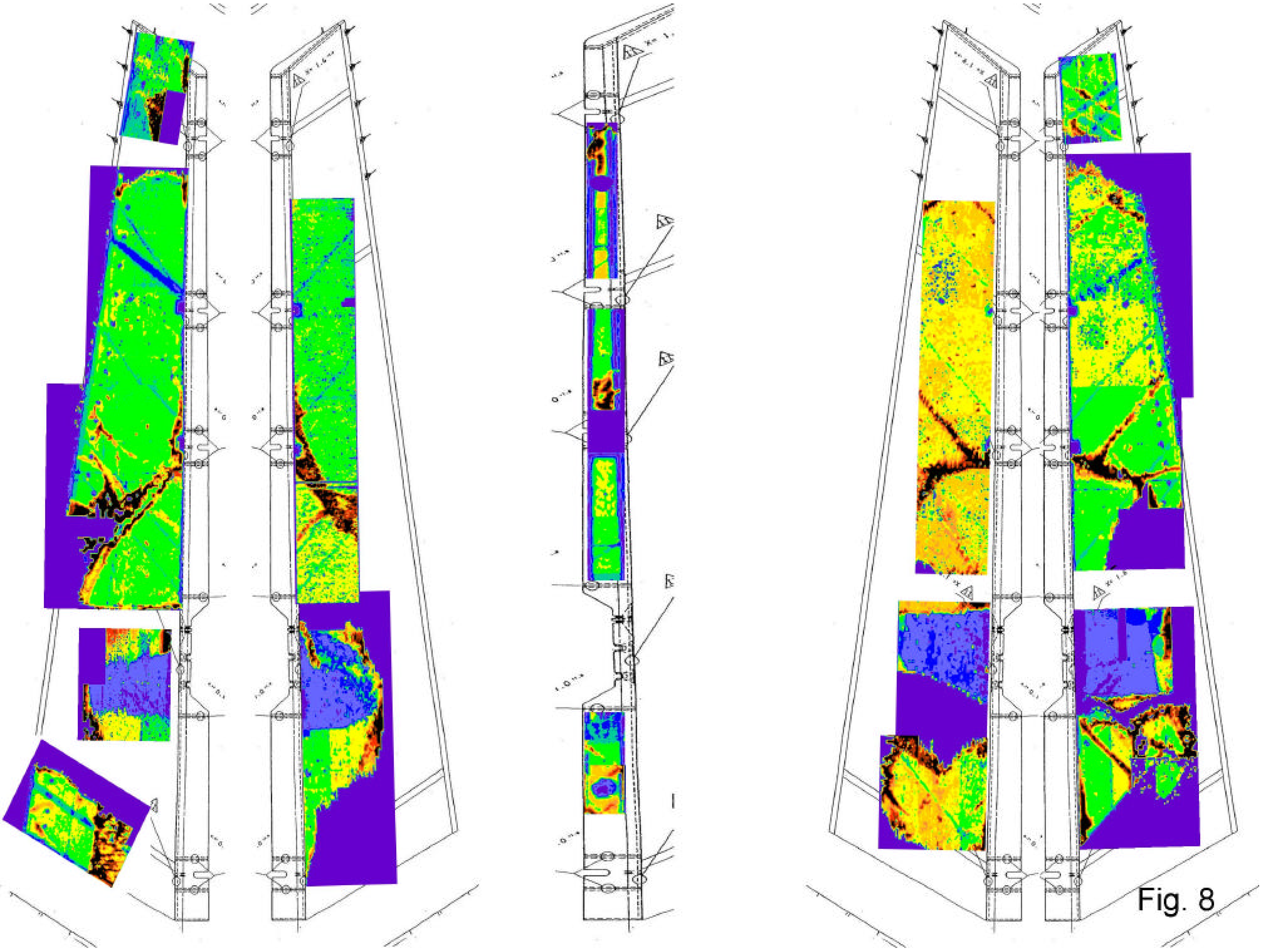


Fig. 8