CHAPTER 5 – EXAMINATION OF FIELD DATA

As part of this study, several NDT dataset from different project sites are used for analyses and tomographic imaging. These data are used in developing strength images according to the methodologies described in Chapter 2-4. The data were obtained from twenty (20) different drilled shaft foundations from three (3) different project sites, including:

- *Existing* dataset from two (2) test drilled shafts with planned defects from NGES, Amherst, Massachusetts;
- *Existing* dataset from twelve (12) production shafts (shafts used in a bridge project with unplanned defects) from Jim Camp Bridge Project, Arizona;
- *New* dataset from four (4) production shafts from Sevenmile Gooseberry Project, Utah.

5.1 STANDARDIZED PRESENTATION OF THE DEFECT CHARACTERIZATION AND IMAGING RESULTS

In this chapter, the NDT results from twenty (20) drilled shafts discussed above are presented in a standardized template display format for comparison. The assumptions and definitions of terms used in the analysis and imaging of the results are explained next.

5.1.1 Standardized Template Format for the Display of Imaging Results

As mentioned in Chapters 2 to 4, a three-step approach for integrity assessment of drilled shafts is developed. This three-step approach is presented herein in a standardized template display. Each standardized template displays, from top to bottom, four distinct sub-templates in the following order:

1. *Current Practice* – This sub-template display standard zero-offset CSL data (velocity/picked time vs. depth) and velocity tomograms **without** velocity equalization applied, which represents current state of practice[5].
2. *Step 1: Anomaly Identification (and independent verification, if dual CSL/GDL testing was performed)* – This sub-template displays the three-dimensional tomograms **after** velocity equalization applied for comparison. Also included is the "roughness model" which measure the spatial derivative (or curvature) of the velocity field.
3. *Step 2: Defect Definition* – Displays velocity histograms and Gaussian curve fits for various defect zones. For multiple levels of defects, velocity distribution curves for different depth levels are examined. The purpose of these curves is to identify cut-off velocities used to define defect volumes.
4. *Step 3: Defect Characterization and Imaging* –In this sub-template, velocity images are presented in unit of strength. Velocity cut-off values for each defect are used to give

[5] For the most part, in the U.S., the "current practice" consists of crosshole sonic logging (CSL). In our displays, the 3-D tomographic inversion without velocity equalization is included under "current practice" even though this is presently an advancement used only on a limited basis in the field.

final volumetric strength images of defects. Empirical fourth power strength to velocity relation (Equation 7) is used. Areas identified as artifacts are not imaged; therefore, the "strength model" and volumetric images represents the final interpretation of shaft condition for the engineer for shaft integrity assessment.

5.1.2 Different Tomographic Inversion Methods

Crosshole sonic data can be acquired using "zero-offset" geometry (standard CSL) with no separation between the source and receiver probe (or in near horizontal plane). Alternatively, sonic data can be acquired using "offset logs" where continuous log measurements are performed with the source or the receiver offset in depth (by some nonzero angle). Therefore tomographic inversion can be performed using zero-offset logs or multi-offset logs.

In addition, tomographic reconstruction can be performed using 2-D or 3-D inversion methods. In 2-D inversion, each test panel is inverted independently. In 3-D inversion, travel time picks from all test panels are inverted simultaneously.

In this study, a velocity equalization procedure is introduced as an important tomography pre-processing quality control (QC) step. Velocity equalization is a process performed prior to tomography that equalizes all offset CSL logs to the same median velocity by applying constant static shifts to the individual logs. Median velocity is calculated using zero-offset CSL logs. It is considered to be a better representative of background shaft velocity than mean (average) velocity because it is less affected by the low velocity anomalies that may be present. The median velocities are indicated as vertical green lines in the "standard zero-offset" CSL logs in the "Current Practice" sub-template. CSL logs are presented in units of velocity versus depth.

In this report, 3-D tomographic inversion results are presented before and after velocity equalization. Only the Amherst-NGES dataset was multi-offset. Dataset from the Jim Camp and Sevenmile Gooseberry Projects were all zero-offset. The 3-D tomographic inversion results are displayed in 3-D, or in other words, in cross-sectional side-by-side view or by a contoured velocity image of a defect volume indicating the shaft condition inside the rebar cage.

5.1.3 Tomographic Processing Parameters

In each figure, processing parameters used in tomographic inversion are tabulated. "Smooth" refers to the smoothing factor used for tomographic data inversion. The higher the number, the smoother the image boundaries become. Low smoothing results in courser and grainier looking images that are suitable for distinguishing subtle anomalies. Tomography inversion is performed for five iterations and the final RMS (root mean square) error is calculated. At each iteration, the RMS value should progressively decrease indicating stable inversion. RMS represents the degree of fit of the observed data to the imaged results (final model). The smoothing and RMS error are provided for the tomography results before and after velocity equalization for comparison.

Equalized median or background "shaft" velocities are also provided in another table for the velocity field before performing tomography (from the offset CSL logs) and after tomography.

These values are provided to examine changes in background velocity as a result of the tomographic inversion.

5.1.4 Anomaly Versus Defect

In this study and in the figures presented in this chapter, "anomaly" refers to a deviation from uniformity in a concrete structure. No determination is yet made regarding its exact size or extent; just identification has been made in a CSL or GDL record (Step 1 above). Ideally, an independent verification (using another logging method like GDL) is needed to determine if the anomaly is not a false positive. Three-dimensional tomographic imaging (CSLT) is performed for imaging these anomalies. Therefore, the term "anomaly" refers to a suspected zone in a CSL, GDL, or CSLT data without determination for its size or extent.

Once a suspected (blue color) "anomaly" zone is identified in a CSLT data, statistical analysis is performed to separate velocity distribution of sound concrete from anomalous concrete (Step 2). With this analysis, a cut-off velocity is obtained that separates the two velocity distributions. Statistical analysis can be performed for multiple depth "zones", which sometimes are overlapping.

Sometimes, no clear distinction between velocity distributions of sound concrete versus velocity distribution of anomalous concrete can be made. In addition, for some shafts a cut-off velocity is obtained that is close to the shaft median velocity (representing sound concrete velocity). In these cases, it is concluded that the "anomaly" is not statistically significant and the shaft is sound at those depths.

For those anomalies that a clear distinction between sound and anomalous concrete can be made, cut-off velocity is used to define a "defect" as the volume of concrete with a velocity lower than the cut-off velocity. Note that, within a given depth zone, none or several defects can be indicated. Therefore, the number of interpreted defects or depth zones used in statistical analysis may not equal to the number of suspected anomalies.

For engineering analysis, defect values are presented in units of strength using velocity to strength empirical relationships. Sound concrete (velocities above the cut-off velocity) is presented at concrete compressive strength, which is assumed as 27,600 kPa (4,000 psi). Velocity contouring is performed to obtain "volumetric imaging of defect" plots at 27,600 kPa (4,000 psi) and at 16,500 kPa (2,400 psi) representing 60% strength. The blue color defects that are indicated in the "strength model" and the imaged defect volumes represent the final interpretation of the data. Whether these defects are structurally significant, however, depends on location, size, and design factors to be determined by modeling by the engineer (integrity assessment).

5.1.5 Artifacts and the Roughness Model

In tomographic images where no velocity equalization is performed, often the final images contain artifacts. Artifacts are erroneous values produced by the tomographic matrix inversion which is non-linear and non-unique. Non-uniqueness in geophysical interpretation and

mathematical modeling refer to a problem for which two or more models satisfy the data equally well. Artifacts can also be a result of inadequate scanning (ray coverage) of the test volume and inaccuracies in travel time picking. These artifacts mostly occur near the image boundaries.

The final 3-D tomography results are presented side by side with an interpretational tool called the "Roughness Model". In the roughness model, the roughness value at a given cell point, is calculated by computing changes in velocity from its six neighboring points (or spatial derivative) and it represents the curvature (or roughness) of the velocity field. It identifies regions where a large change in velocity values has taken place. It is included in the figures as a means of assessing the stability of the tomographic inversion process (along with the RMS error and smoothing factors used) and as an interpretational tool for distinguishing anomalies from artifacts, which typically exhibit high localized roughness.

5.1.6 Narrative Description of Each Figure

For each dataset, the field results are described using similar standardized logic. First, from each figure, the suspected "anomalies" are identified from the CSL data as low velocities zones. The anomalies are numbered sequentially. Next, the same anomalies are examined in the three-dimensional tomographic inversion CSLT images before and after velocity equalization, noting inversion artifacts and the roughness model. Statistical analysis is analyzed to define cut-off velocities as compared to median velocities. This analysis is examined separately for different anomalies at different depth zones. The number of depth zones may not correspond to the number of anomalies as a depth zone may contain several anomalies. Finally, the strength model is explained which presents the interpreted blue color "defects'. Defects are referenced using the same numbering system used in defining anomalies. Velocity contouring is described for imaging interpreted defect volume at 27,600 kPa (4,000 psi), representing breaking strength of assumed sound concrete; and, as an example, 16,500 kPa (2,400 psi) for 60% strength concrete.

5.2 AMHERST NGES RESULTS

Six drilled shafts were constructed at the NGES site during March and April, 2000. The shafts contained both built-in and unplanned defects (Iskander, et al., 2000). Built-in defects include necking, voids, caving, and soft bottoms.

CSL/CSLT data for the original NGES study was collected by InfraSeis, Inc.. Although the data was collected about one year from the shaft construction, no tube debonding was indicated.

In the next section, CSL and CSLT results from two of the Amherst-NGES drilled shaft study (Shaft 1 and Shaft 4) are presented. Both shafts had a diameter of 0.9 m and a length of about 15.2 m (50 feet). Four CSL steel access tubes were attached to the rebar cage in an approximately symmetrical pattern. Therefore, field data was collected from six separate CSL paths (or panel combinations) consisting of four perimeter paths and two diagonal paths.

For each test panel, seven offset CSL logs were produced: zero offset; three positive offset; and, three negative offsets. In these panels, 0º CSL logs was combined with approximately ±26º, ±45º, and ±60º offset logs. Therefore, for each shaft, the acquisition geometry included a total of 42 offset CSL logs (=6 panel combinations x 7 offset logs).

Results from the Amherst test site are summarized below.

5.2.1 Amherst NGES, Shaft 1 (Figure 46)

1. *Current Practice* – Standard CSL (velocity vs. depth) indicates three suspected "anomalies":
   Anomaly 1: 2-3 m depth and mostly between Tubes 1 and 2;
   Anomaly 2: 8-8.5 m depth and mostly between Tubes 2 and 3;
   Anomaly 3: 14-15 m depth and mostly between Tubes 2, 3, and 4.
   Multi-offset (7-offsets) 3-D CSLT tomography, with no velocity equalization, images CSL Anomalies 1 and 3 but not Anomaly 2.
2. *Anomaly Identification* – Multi-offset CSLT with velocity equalization better resolves Anomalies 1 and 3. Slight indication for Anomaly 2 is now indicated in both the CSLT image and the roughness model. Also, a small anomaly (0-0.5 m) near the shaft surface is indicated (Anomaly 0).
3. *Defect Definition* – Three depth zones are selected (to examine the four Anomalies 0-3) and velocity cut-off values are indicated using 2 and 3 Gaussian fits to the velocity histogram.
4. *Defect Characterization and Imaging* – Four blue color "defects" zones are interpreted in the strength model. Volumetric images indicate only Defects 0, 1, and 3 between 0-0.5 m, 2-3 m, and 14-15 m depths, respectively are of low strength (<16,500 kPa (2,400 psi)).

Comments. Next to the strength model, a cross-section is provided indicating actual locations of planned defects and a description of the defects. Six defects were pre-planned with only two defects (planned Defects D and F) were located inside the rebar cage. Tomography clearly imaged the planned defects D and F as well as planned Defect A. The planned Defect A was a plastic bucket located outside the cage which is clearly imaged by CSLT. Again note a slight indication of an unplanned low velocity defect near the surface (0-0.5 m) close to Tube 3.

5.2.2 Amherst NGES, Shaft 4 (Figure 47)

1. *Current Practice* – Standard CSL indicates four suspected "anomalies":
   Anomaly 1: 2.5-3 m depth and mostly between Tubes 3 and 4;
   Anomaly 2: 5-6 m depth and mostly between Tubes 3 and 4;
   Anomaly 3: 9.2-9.8 m depth and mostly between Tubes 3 and 4;
   Anomaly 4: 14.5-15 m depth and mostly between Tubes 2, 3, and 4.
   Multi-offset tomography (CSLT), with no velocity equalization, images Anomalies 1 and 2 but not Anomalies 3 and 4 (only a slight indication is observed).
2. *Anomaly Identification* – Multi-offset CSLT with velocity equalization better resolves Anomalies 1, 2 and 4. Slight indication for Anomaly 3 is indicated in both the CSLT image and the roughness model.

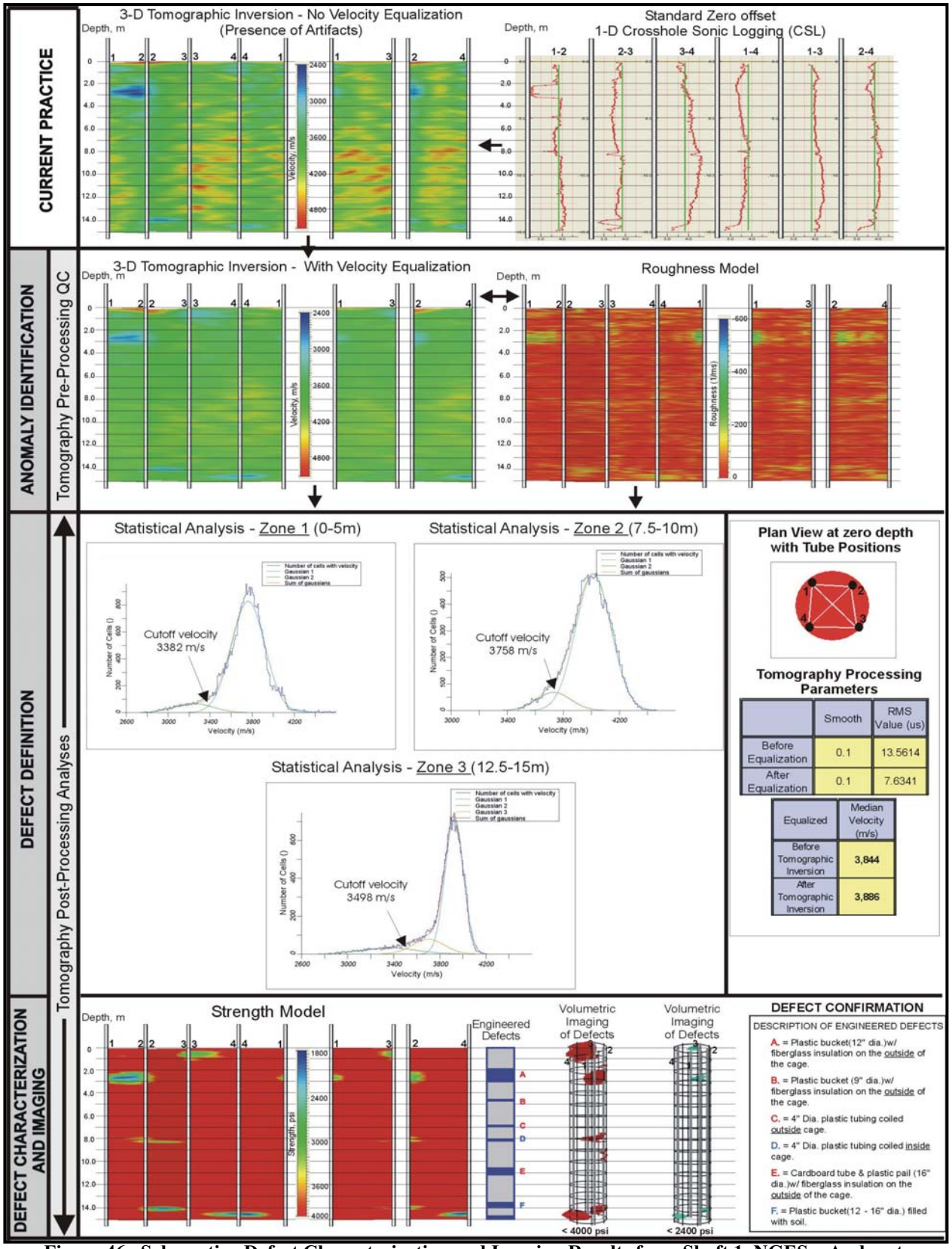

Figure 46. Schmeatic. Defect Characterization and Imaging Results from Shaft 1, NGES – Amherst.

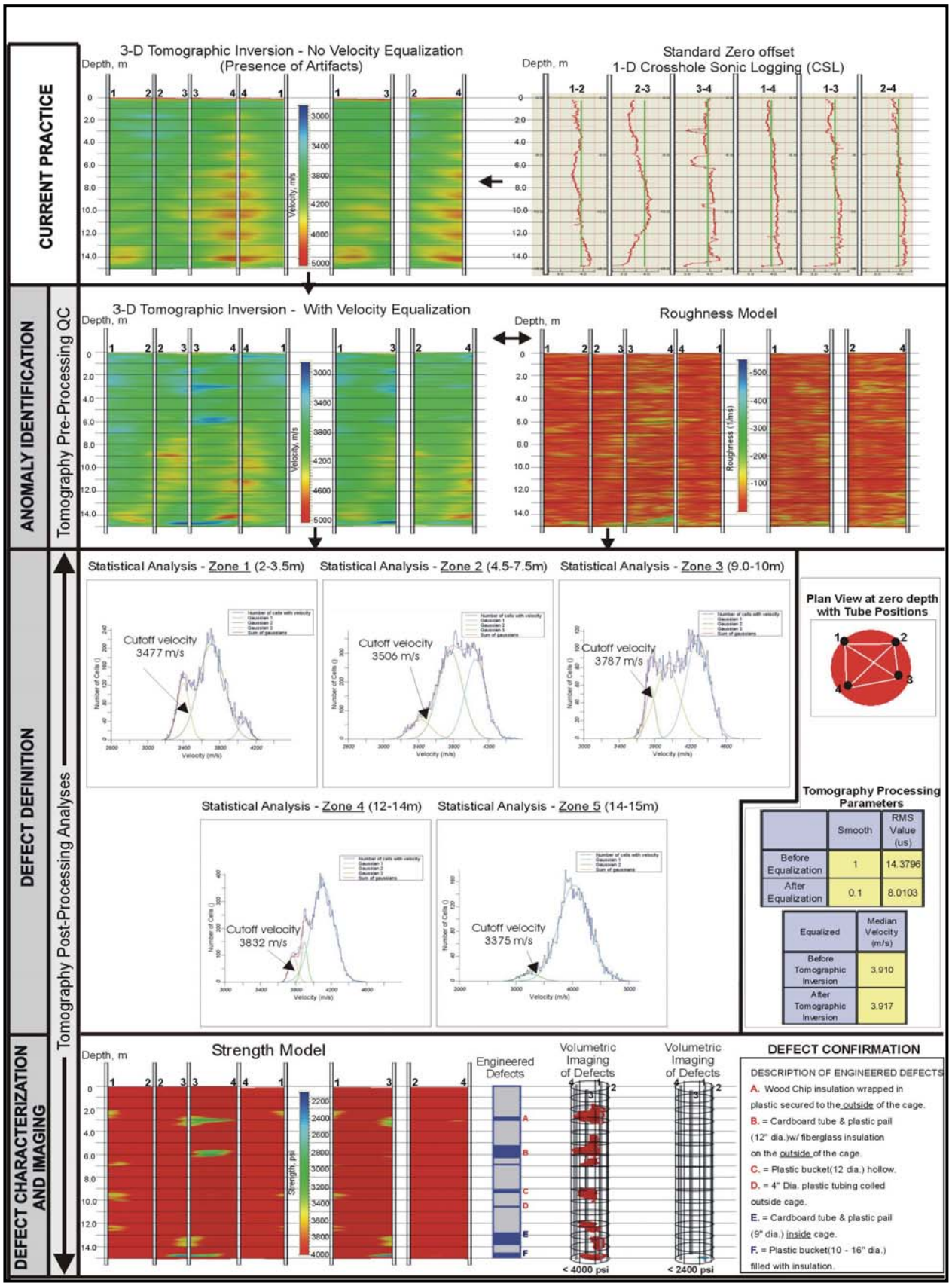

Figure 47. Schematic. Defect Characterization and Imaging Results from Shaft 4, NGES – Amherst.

3. *Defect Definition* – Five depth zones are selected and velocity cut-off values are indicated using 2 and 3 Gaussian fits to the velocity histogram. Anomalies 3 and 4 have a cut-off velocities close to median velocity (3,917 m/s) and; therefore, not statistically significant.
4. *Defect Characterization and Imaging* – Three (3) green-blue color "defects" zones are interpreted in the strength model (Defects 1, 2, and 4). Other minor defects are indicated by yellow-orange colors. Volumetric images indicate only Defect 4, between 14.5-15 m depth, is of low strength (<16,500 kPa (2,400 psi)).

Comments. Next to the strength model, a cross-section is provided indicating actual locations of planned defects and a description of the defects. Six defects were pre-planned with only two defects (planned Defects E and F) were located inside the rebar cage. Tomography clearly imaged the planned Defect F as well as exterior planned Defects A and B. Minor indication of exterior planned Defects C and E are also observed (yellow color).

5.3 JIM CAMP BRIDGE RESULTS

Jim Camp Wash Bridge project site was located on the Petrified Forest National Park, east of Holbrook, Arizona. Jim Camp Bridge was designed using two (2) abutments and four (4) pier lines each supported by two (2) drilled shafts. Each drilled shaft had a diameter of 0.76 m (2.5 ft) and each contained three (3) 50.8 mm (2 in) I.D. steel access tubes.

As indicated in Figure 48, all shafts were tested during February – March, 2002 using only zero offset CSL. CSL data was collected by EarthSpectives, Inc. In addition to standard CSL, subsequently gamma-gamma density logging (GDL) data was collected by AMEC, Inc for Pier 2, Shaft B. The GDL logs were acquired to evaluate if the concrete integrity was jeopardized by problems that occurred during shaft construction.

5.3.1 Description of UPV Testing Results Overview

Ultrasonic Pulse Velocity (UPV) test was performed prior to the CSL field work. Table 3 presents the UPV test results for concrete samples obtained from the original mix between 2 to 7

Table 3. UPV Testing Results on Concrete Cylinders.

	Day # 2 Velocity (m/s)	Day # 3 Velocity (m/s)	Day # 4 Velocity (m/s)	Day # 5 Velocity (m/s)	Day # 6 Velocity (m/s)	Day # 7 Velocity (m/s)
Center	4158.7	4336.7	4299.9	4355.3	4399.4	4269.7
L. side	4158.7	4234.0	4269.7	4330.5	4374.1	4299.9
R. side	4210.5	4170.1	4228.1	4216.4	4257.7	4281.7
Average	4175.97	4346.93	4265.90	4300.73	4343.73	4283.77
Center	4124.8					4318.2
L. side	4222.2					4263.7
R. side	4141.7					4305.9
Average	4162.90					4295.93
Average Velocity	4169.43	4346.93	4265.90	4300.73	4343.73	4289.85

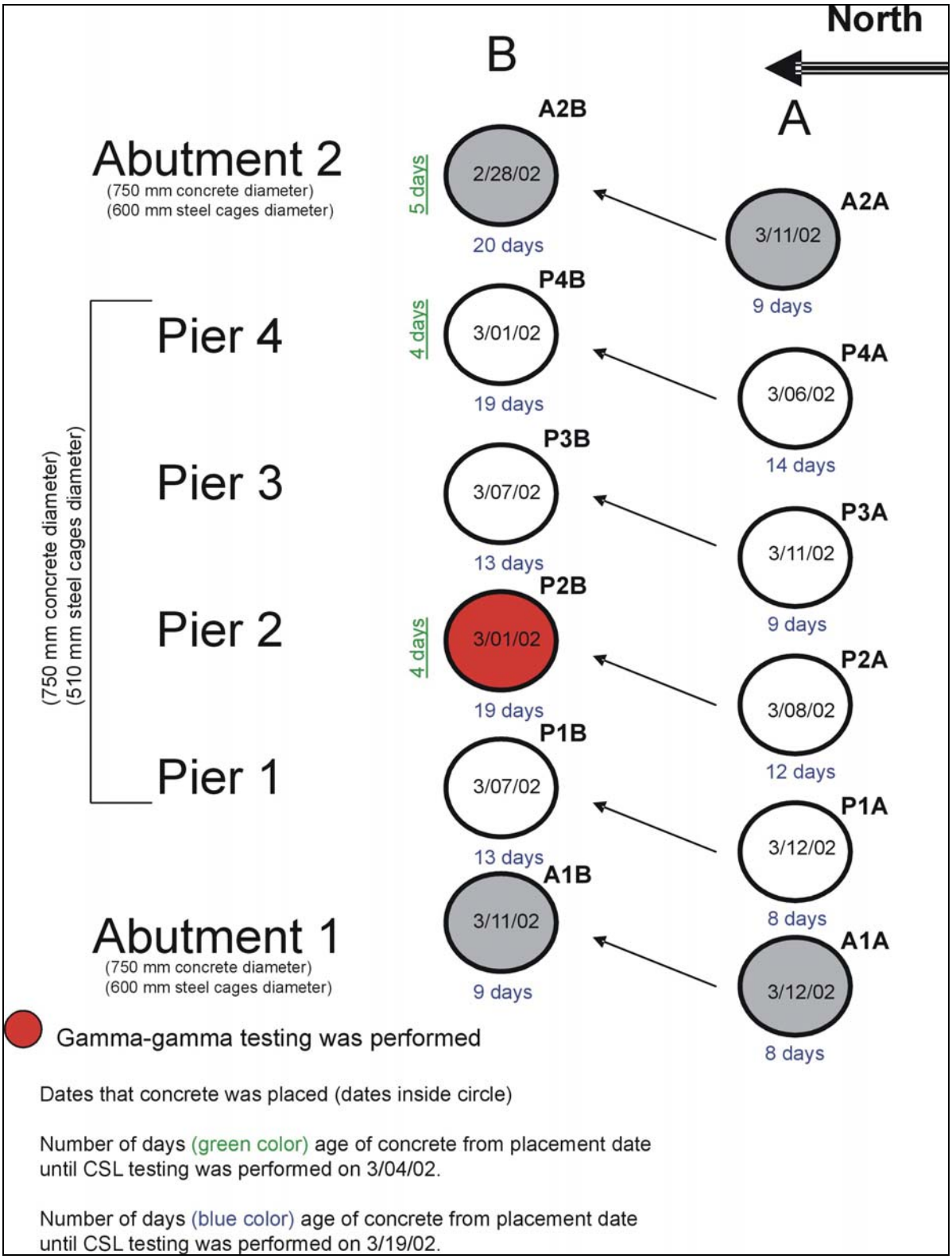

Figure 48. Schematic. Plan View of the Drilled Shafts at the Jim Camp Bridge, AZ.

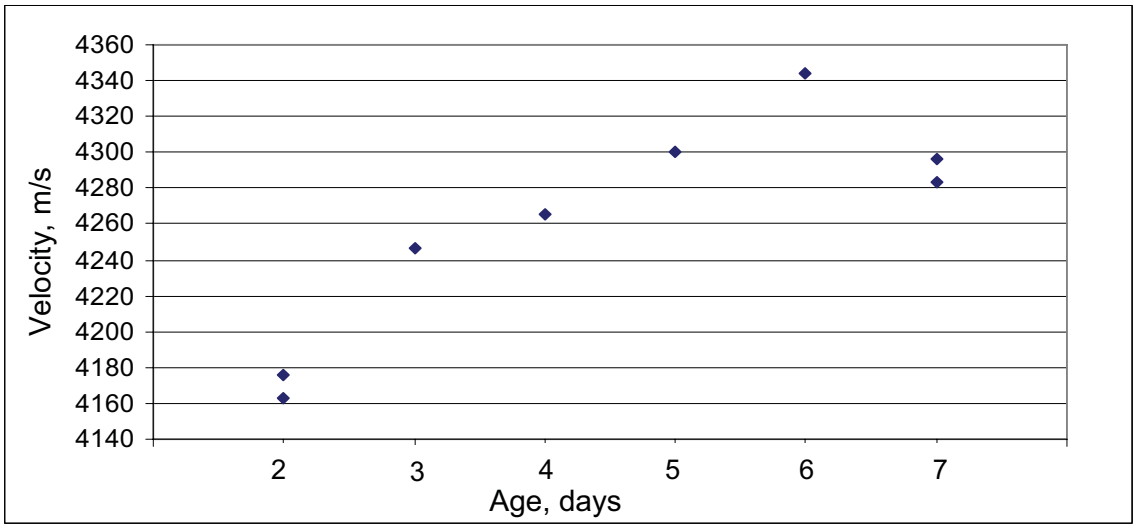

Figure 49. Graph. UPV Velocities Versus Age.

days of age. The velocities were measured on the concrete cylinders of 0.1524 x 0.3048 m (6 x 12 in) in size. Three measurements were taken from each cylinder: at the center, and from the left and right sides with the results presented in Figure 49. An average UPV velocity of 4,280 m/s is indicated for the laboratory samples. CSL testing was performed with more than 7 days of concrete age. However, CSL velocities from the drilled shafts indicated average velocity values less than the average 7-day UPV velocity of 4,280 m/s (please refer to section 4.2).

CSL results from the Jim Camp Bridge site are summarized below:

5.3.2 Jim Camp Bridge, Shaft A1A (Figure 50)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset. Zero-offset tomography (CSLT), with no velocity equalization, indicates un-balanced velocity panels with artifacts in the CSLT images, probably due to errors in measuring tube offsets in the field.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels. A low velocity zone is indicated between 0.2-1 m around Tube 3.
3. *Defect Definition* – No single cut-off velocity can be defined. Shaft is sound.
4. *Defect Characterization and Imaging* – No defects are indicated.

5.3.3 Jim Camp Bridge, Shaft A1B (Figure 51)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset. Zero-offset tomography (CSLT), with no velocity equalization, indicates un-balanced velocity panels with artifacts in the CSLT images, probably due to errors in measuring tube offsets in the field.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels. A low velocity zone is indicated between 0.2-0.7 m around Tube 2 with slight indication in the roughness model.

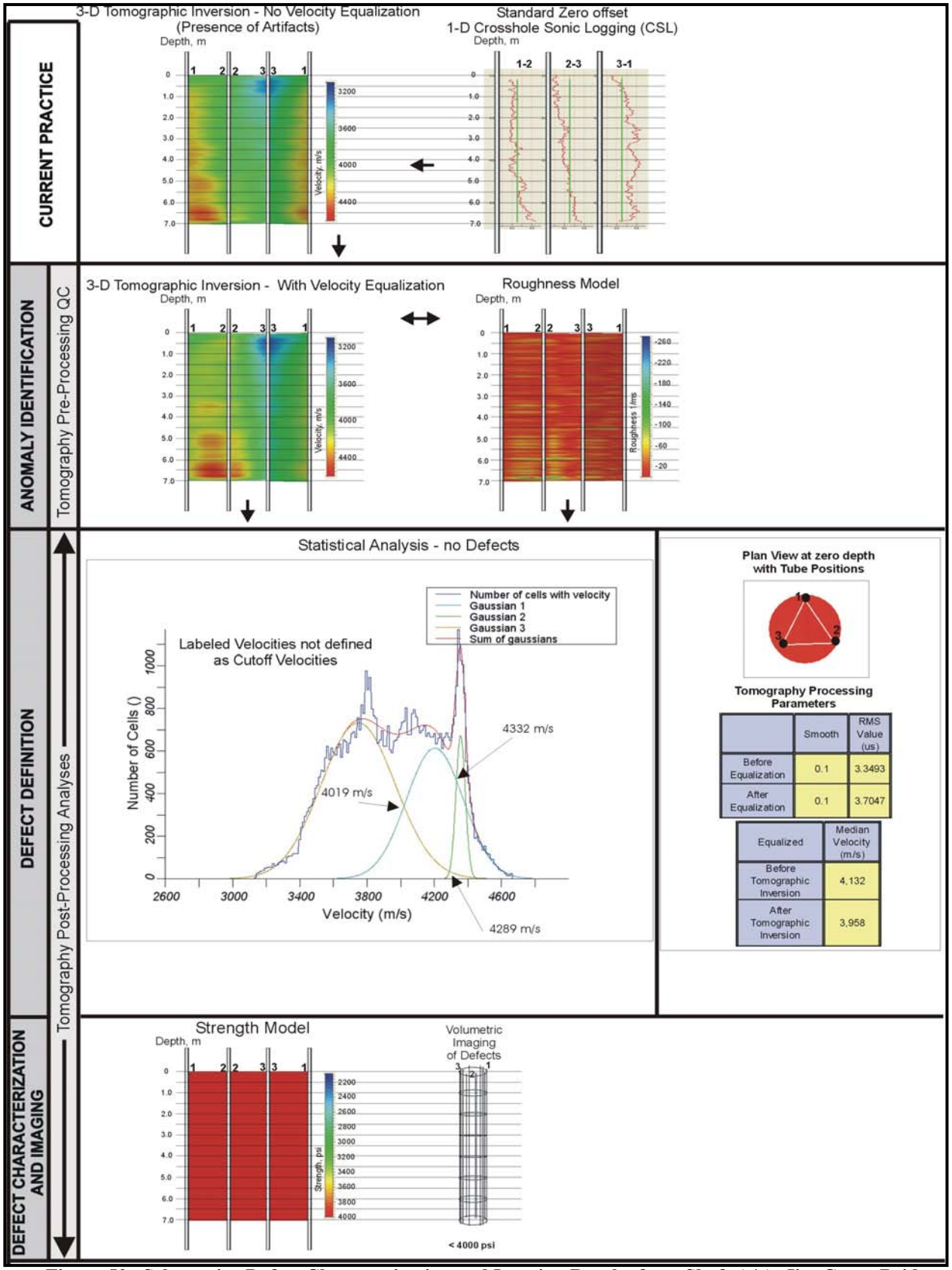

Figure 50. Schematic. Defect Characterization and Imaging Results from Shaft A1A, Jim Camp Bridge.

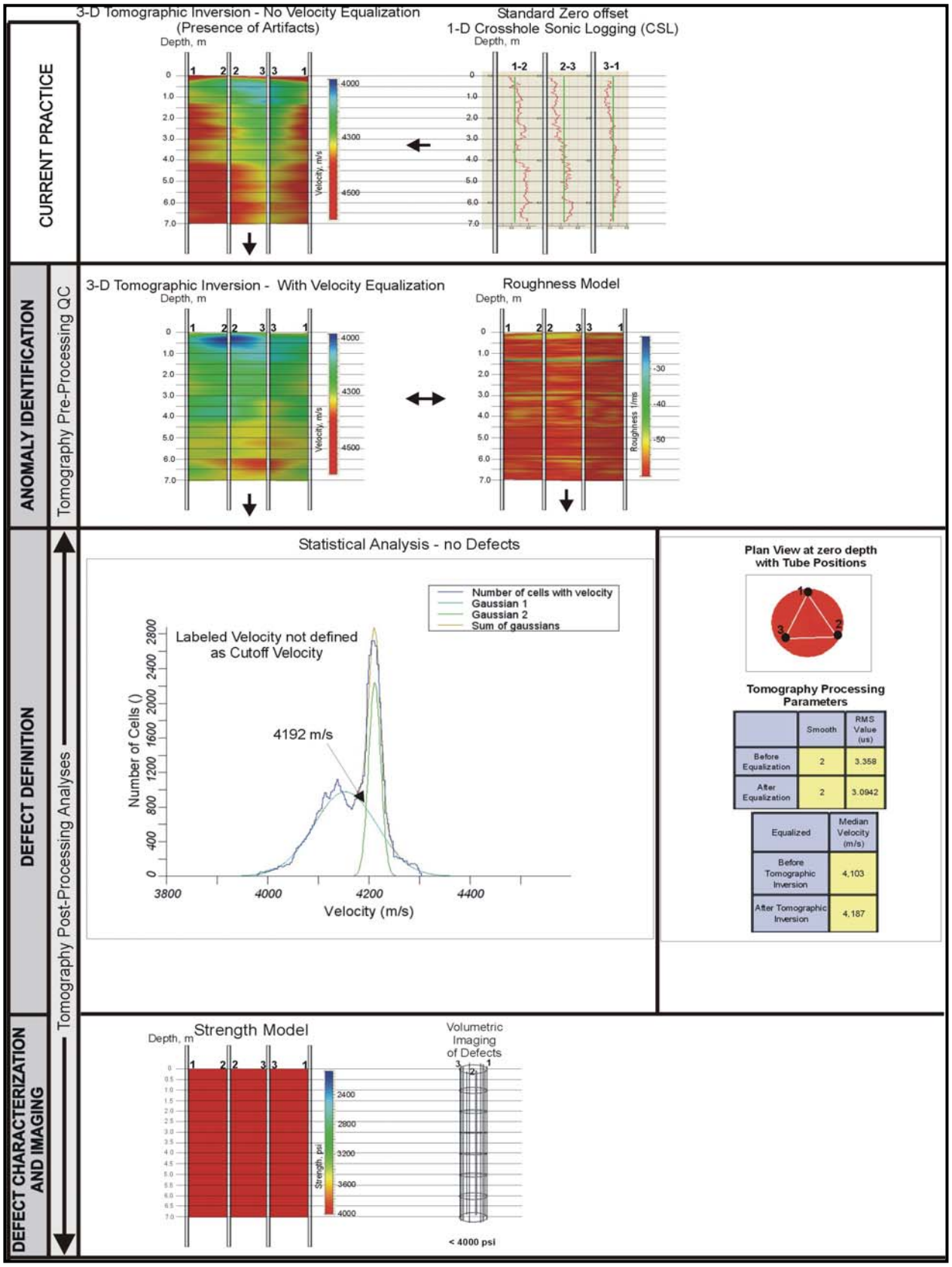

Figure 51. Schematic. Defect Characterization and Imaging Results from Shaft A1B, Jim Camp Bridge.

3. *Defect Definition* – A single cut-off velocity of 4,192 m/s is obtained for the whole shaft which is close to the shaft median velocity (4,187 m/s).
4. *Defect Characterization and Imaging* – No defects are indicated.

5.3.4 Jim Camp Bridge, Shaft A2A (Figure 52)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset. Zero-offset tomography (CSLT), with no velocity equalization, indicates un-balanced velocity panels with artifacts in the CSLT images, probably due to errors in measuring tube offsets in the field.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels.
3. *Defect Definition* – Two zones are selected and velocity cut-off values are indicated using 2 and 3 Gaussian fits to the velocity histogram. One anomaly between 0-3 m in depth has a cut-off velocity 3,836 m/s close to median velocity of 4,150 m/s, and; therefore, may not be statistically significant.
4. *Defect Characterization and Imaging* – One small defect between 0.2-0.5 m near Tube 1 is indicated. Volumetric images indicate that this defect is of high relative strength (>16,500 kPa (2,400 psi)).

5.3.5 Jim Camp Bridge, Shaft A2B (Figure 53)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset. Zero-offset tomography (CSLT), with no velocity equalization, indicates a low velocity zone between Tubes 1 and 2.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels and also confirms the low velocity zone between 0.2-1 m with slight indication in the roughness model.
3. *Defect Definition* – Two zones are selected and velocity cut-off values are obtained close to median velocity using 2 and 3 Gaussian fits to the velocity histogram.
4. *Defect Characterization and Imaging* – No defects are indicated.

5.3.6 Jim Camp Bridge, Shaft P1A (Figure 54)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset. Zero-offset tomography (CSLT), with no velocity equalization, indicates a low velocity zone between Tubes 2 and 3.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels also confirms the low velocity zone between 0.5-1 m with slight indication in the roughness model.
3. *Defect Definition* – A single cut-off velocity of 4,401 m/s is obtained for the whole shaft which is close to shaft median velocity (4,428 m/s).
4. *Defect Characterization and Imaging* – No defects are indicated.

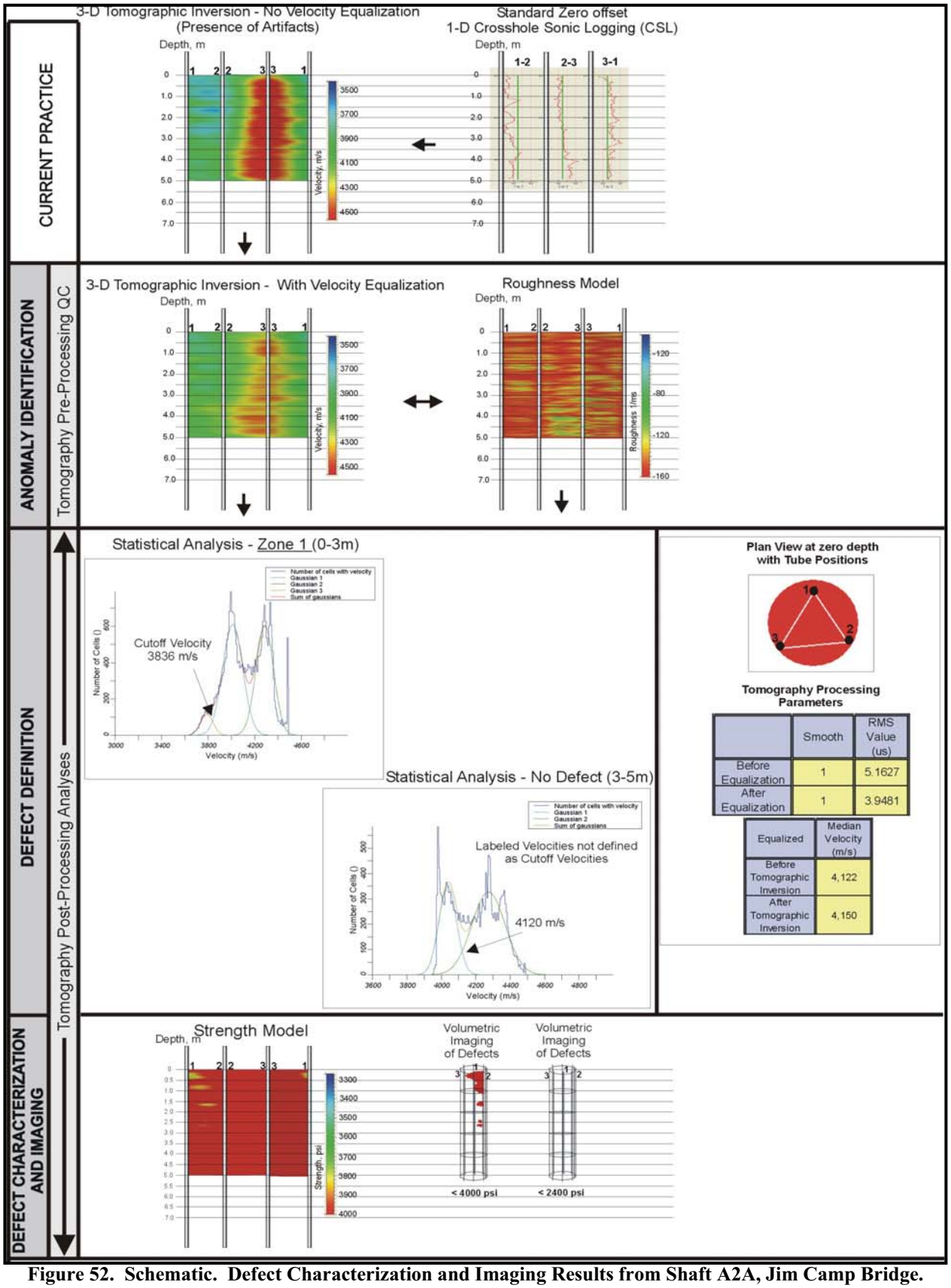

Figure 52. Schematic. Defect Characterization and Imaging Results from Shaft A2A, Jim Camp Bridge.

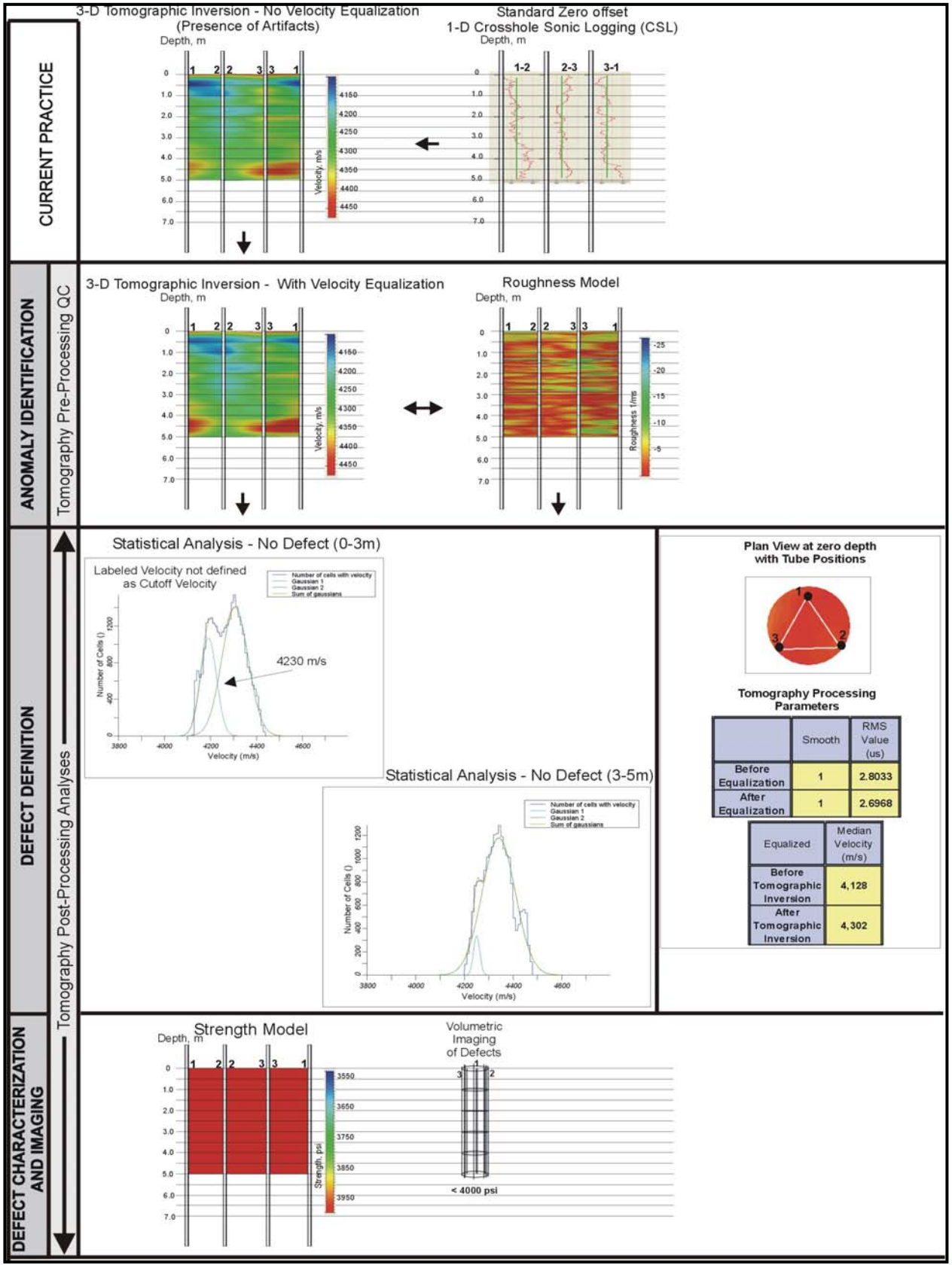

Figure 53. Schematic. Defect Characterization and Imaging Results from Shaft A2B, Jim Camp Bridge.

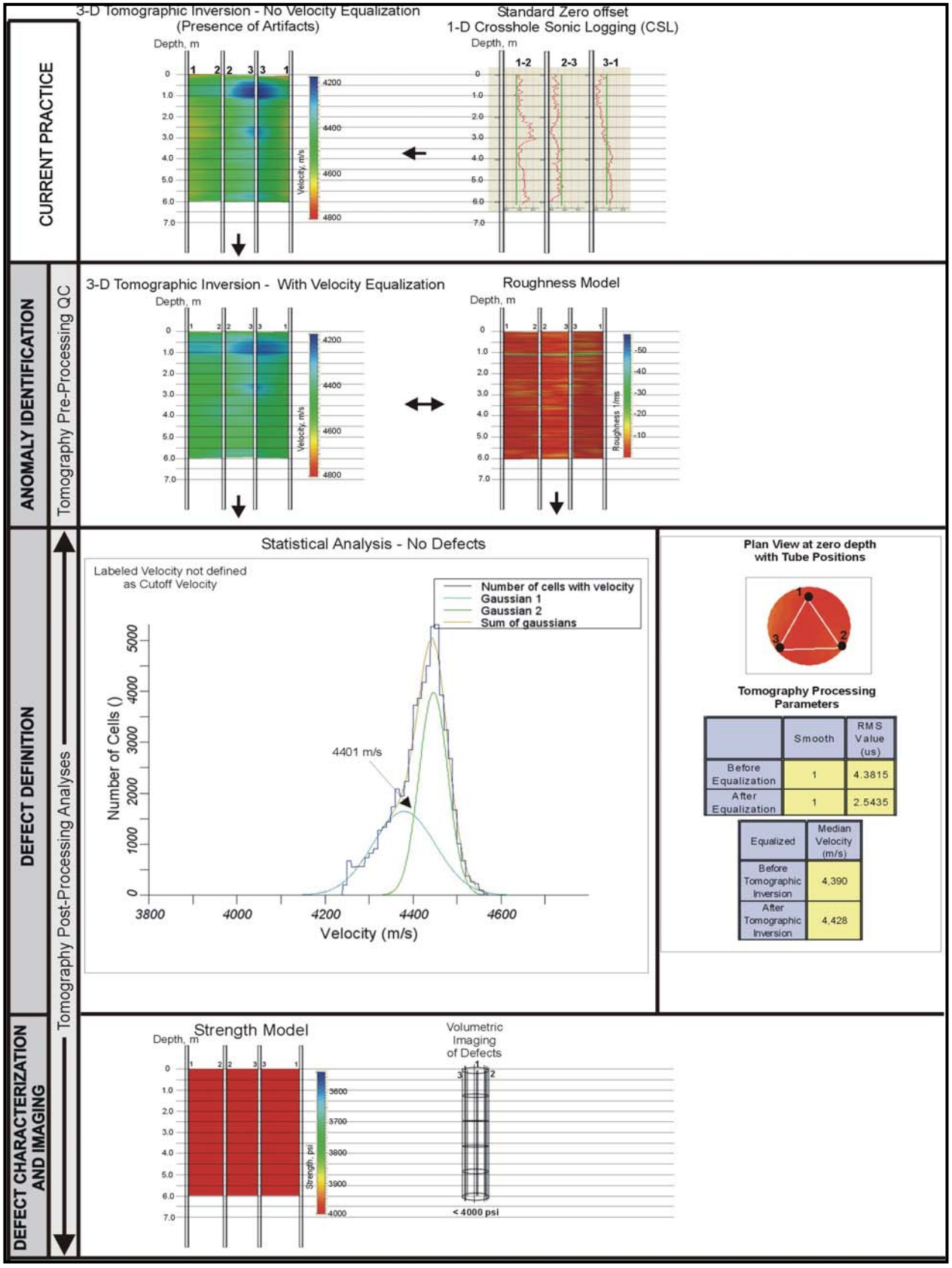

Figure 54. Schematic. Defect Characterization and Imaging Results from Shaft P1A, Jim Camp Bridge.

5.3.7 Jim Camp Bridge, Shaft P1B (Figure 55)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset. Zero-offset tomography (CSLT), with no velocity equalization, indicates a low velocity zone near Tube 2.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels also confirms the low velocity zone between 0.5-1 m with slight indication in the roughness model.
3. *Defect Definition* – A single cut-off velocity of 4,293 m/s is obtained for the whole shaft which is close to shaft median velocity (4,410 m/s).
4. *Defect Characterization and Imaging* – One small defect between 0.2-1 m near Tube 2 is indicated. Volumetric images indicate that this defect is of high relative strength (>16,500 kPa (2,400 psi)).

5.3.8 Jim Camp Bridge, Shaft P2A (Figure 56)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, indicates two low velocity zones between Tubes 2 and 3 between 0.5-0.8 m and 5-5.5 m.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels and the apparent low velocity zones.
3. *Defect Definition* – No single cut-off velocity could be obtained for the whole shaft.
4. *Defect Characterization and Imaging* – No defects are indicated.

5.3.9 Jim Camp Bridge, Shaft P2B (Figure 57)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, indicates a low velocity zone near Tube 3 between 0-1 m.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels and the apparent low velocity zone.
3. *Defect Definition* – A single cut-off velocity of 4,130 m/s is obtained for the whole shaft which is close to the shaft median velocity (4,238 m/s).
4. *Defect Characterization and Imaging* – No defects are indicated.

5.3.10 Jim Camp Bridge, Shaft P3A (Figure 58)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, indicates un-balanced velocity panels in the CSLT images, probably due to the tube positioning errors.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels and an apparent low velocity anomaly is indicated between 0.2-1.0 m depths.
3. *Defect Definition* – A single cut-off velocity of 4,102 m/s is obtained for the whole shaft which is close to the shaft median velocity (4,240 m/s).
4. *Defect Characterization and Imaging* – No defects are indicated.

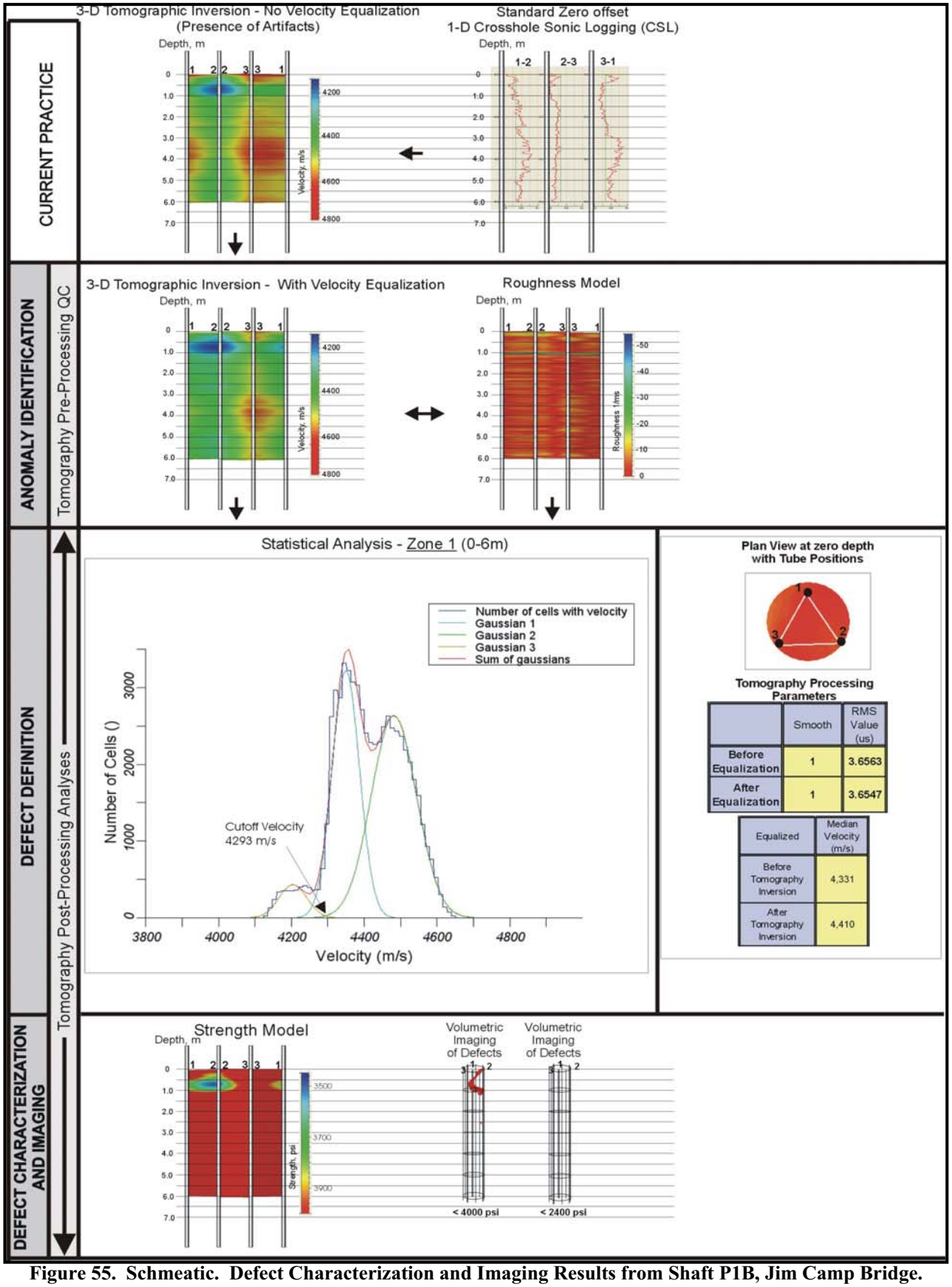

Figure 55. Schmeatic. Defect Characterization and Imaging Results from Shaft P1B, Jim Camp Bridge.

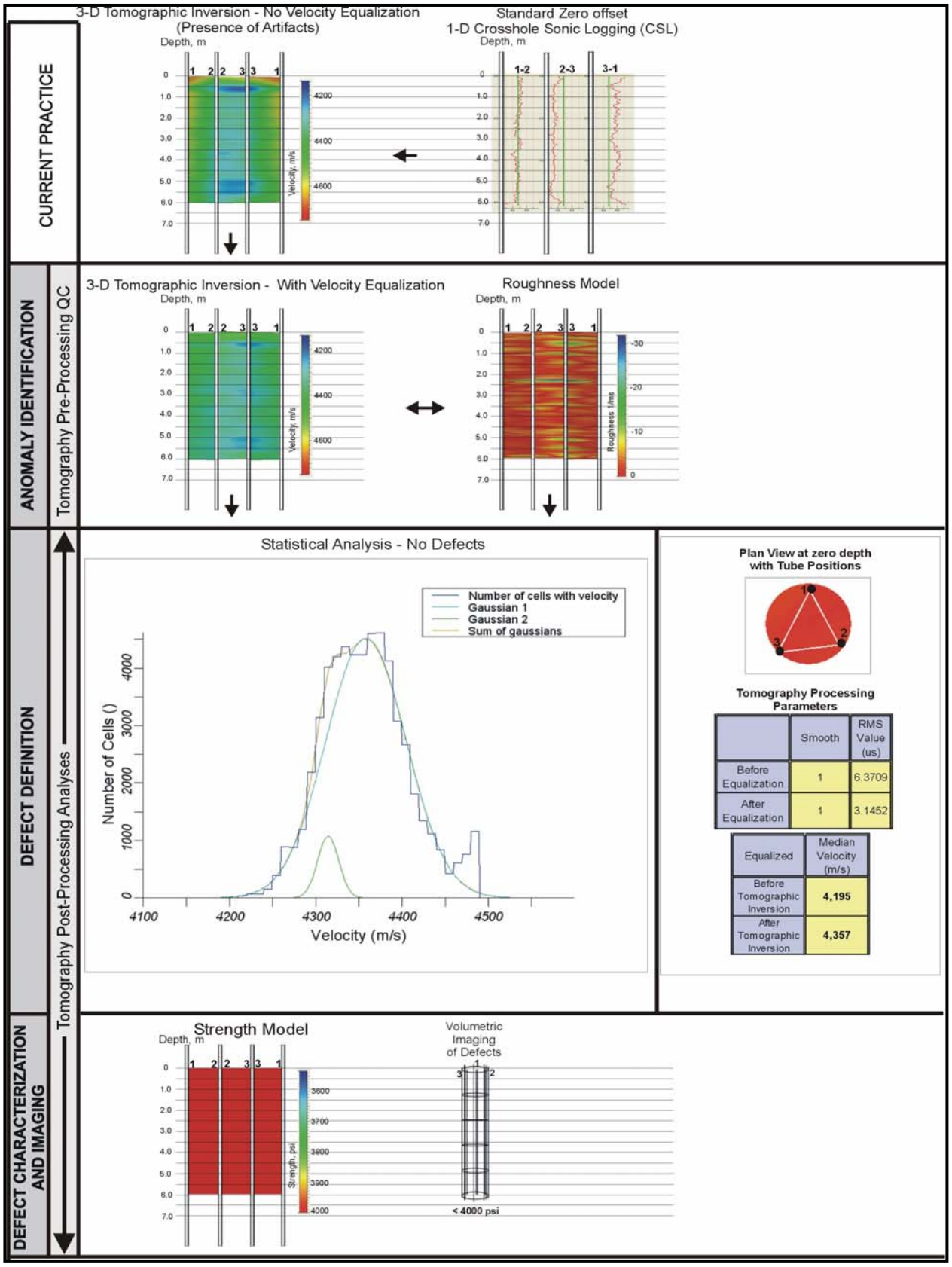

Figure 56. Schematic. Defect Characterization and Imaging Results from Shaft P2A, Jim Camp Bridge.

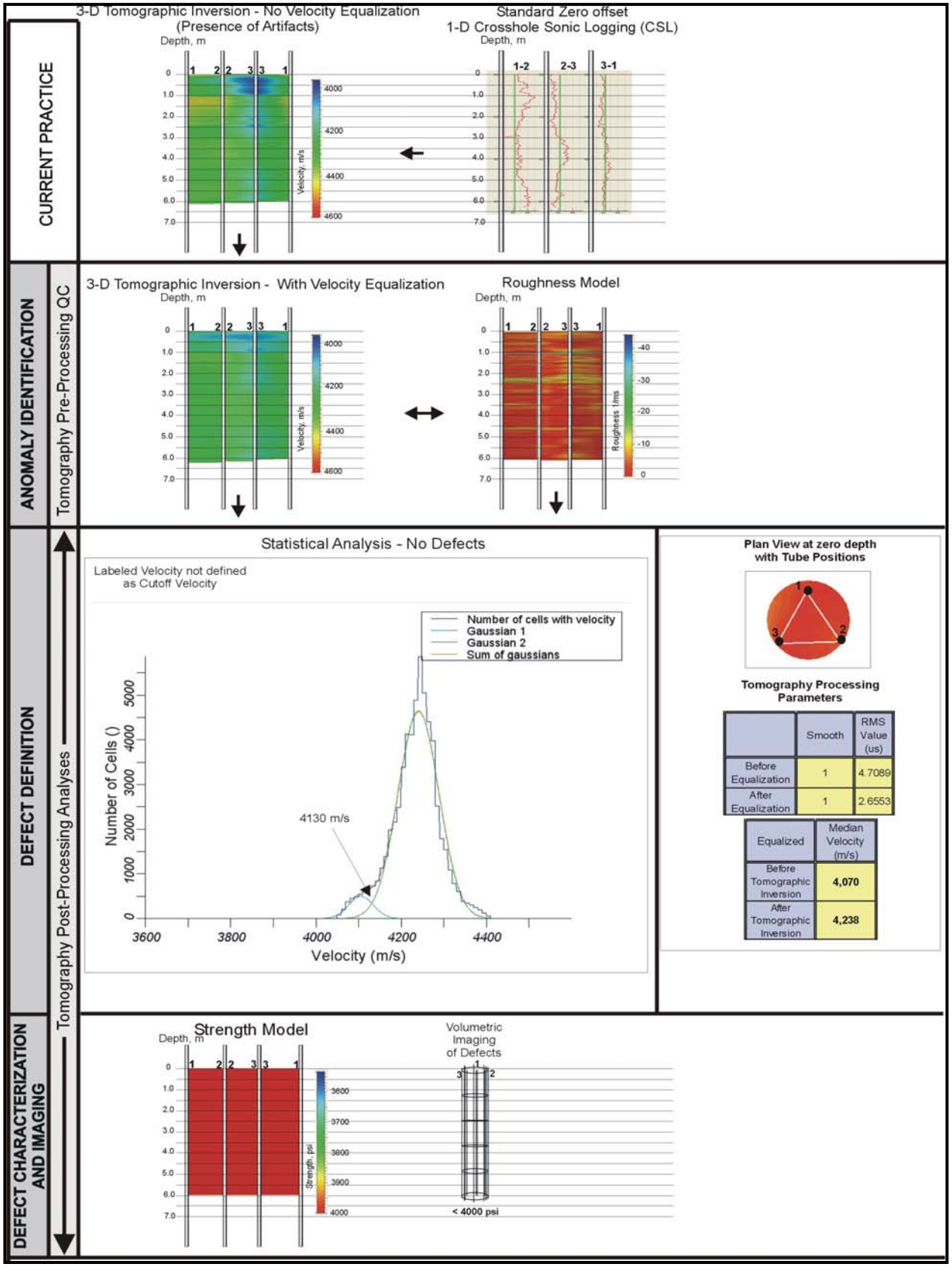

Figure 57. Schematic. Defect Characterization and Imaging Results from Shaft P2B, Jim Camp Bridge.

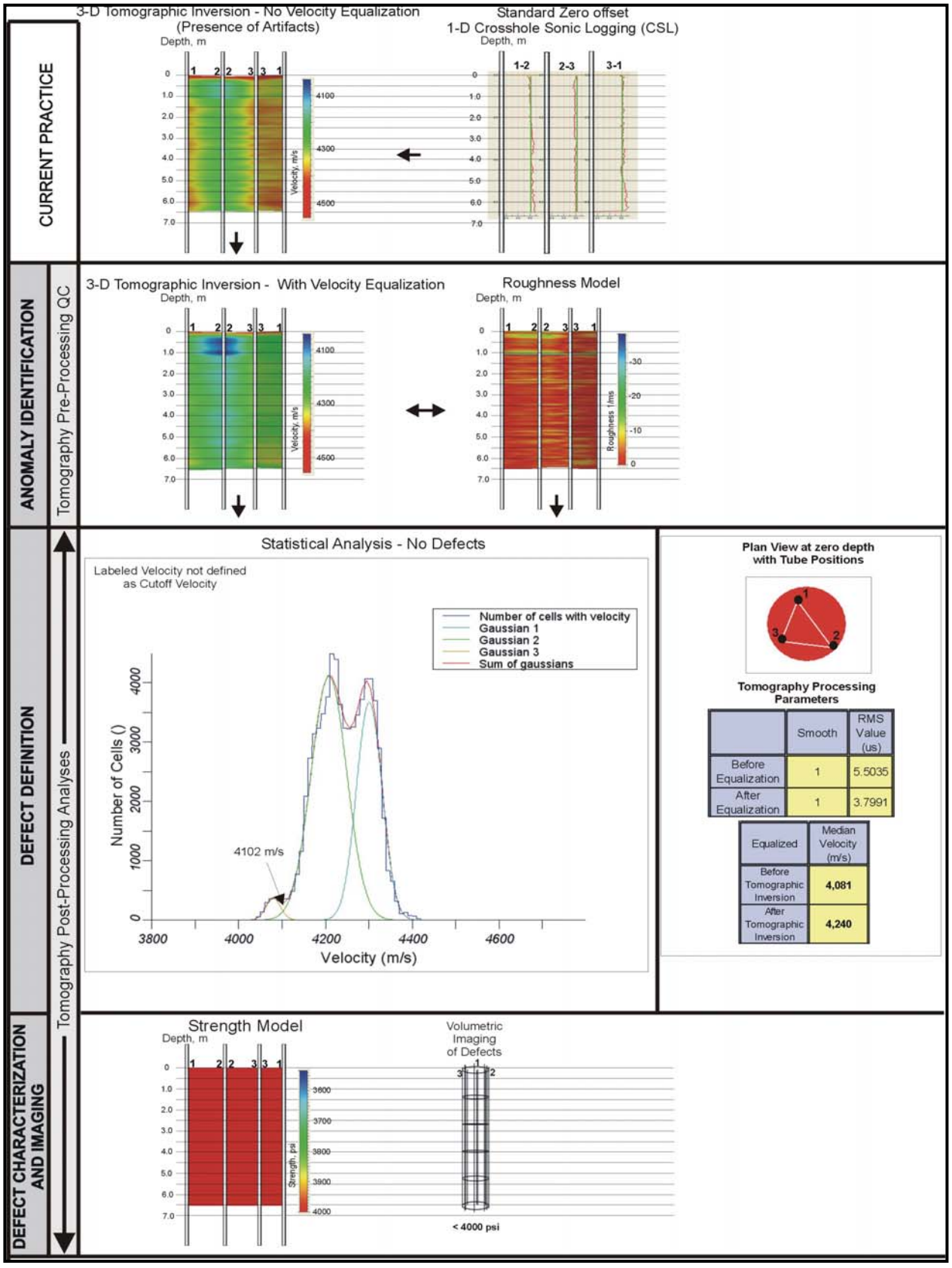

Figure 58. Schematic. Defect Characterization and Imaging Results from Shaft P3A, Jim Camp Bridge.

5.3.11 Jim Camp Bridge, Shaft P3B (Figure 59)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, indicates slightly un-balanced velocity panels in the CSLT images.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels and an apparent low velocity zone indicated between 0.3-1.0 m depths.
3. *Defect Definition* – A single cut-off velocity of 4,400 m/s is obtained for the whole shaft which is about equal to the shaft median velocity (4,428 m/s).
4. *Defect Characterization and Imaging* – No defects are indicated.

5.3.12 Jim Camp Bridge, Shaft P4A (Figure 60)

1. *Current Practice* – Standard CSL indicates no anomalies, just irregular CSL dataset.
   Zero-offset tomography (CSLT), with no velocity equalization, indicates a low velocity zone between 0.5-1 m.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels also confirms the low velocity zone near Tube 2 with slight indication in the roughness model.
3. *Defect Definition* – Two zones are selected and velocity cut-off values are indicated using 2 and 3 Gaussian fits to the velocity histogram. Anomaly 1 (0-2 m) has a cut-off velocity of 3,800 m/s, which is close to shaft median velocity of 4,067 m/s.
4. *Defect Characterization and Imaging* – One small defect between 0.2-1 m near Tube 2 is indicated. Volumetric images indicate that this defect is of high relative strength (~27,600 kPa (4,000 psi)).

5.3.13 Jim Camp Bridge, Shaft P4B (Figure 61)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, indicates un-balanced velocity panels in the CSLT images.
2. *Anomaly Identification* – Zero-offset CSLT with velocity equalization balances the velocity panels.
3. *Defect Definition* – A single cut-off velocity of 4,128 m/s is obtained for the whole shaft which is close to the shaft median velocity (4,299 m/s).
4. *Defect Characterization and Imaging* – No defects are indicated.

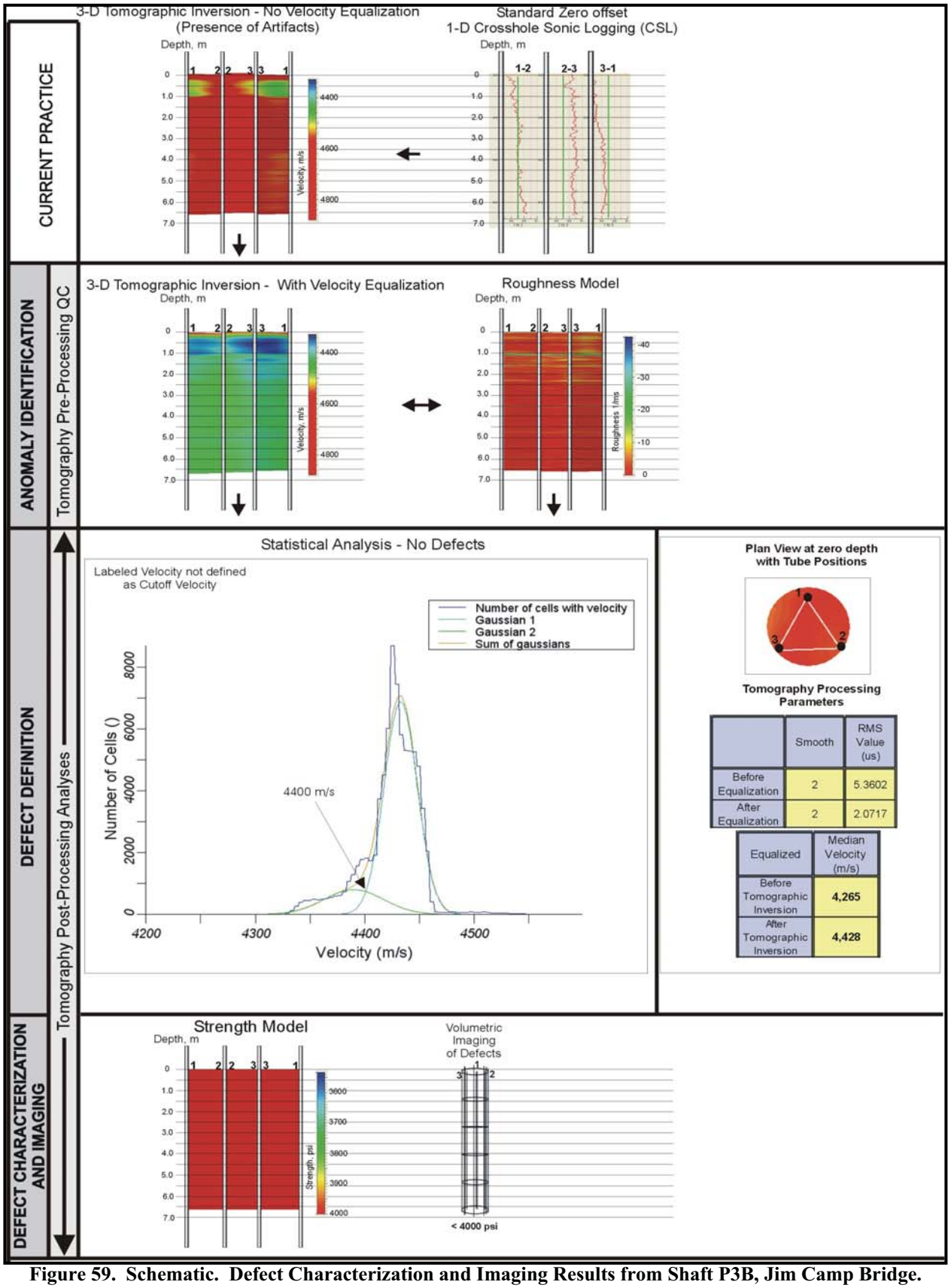

Figure 59. Schematic. Defect Characterization and Imaging Results from Shaft P3B, Jim Camp Bridge.

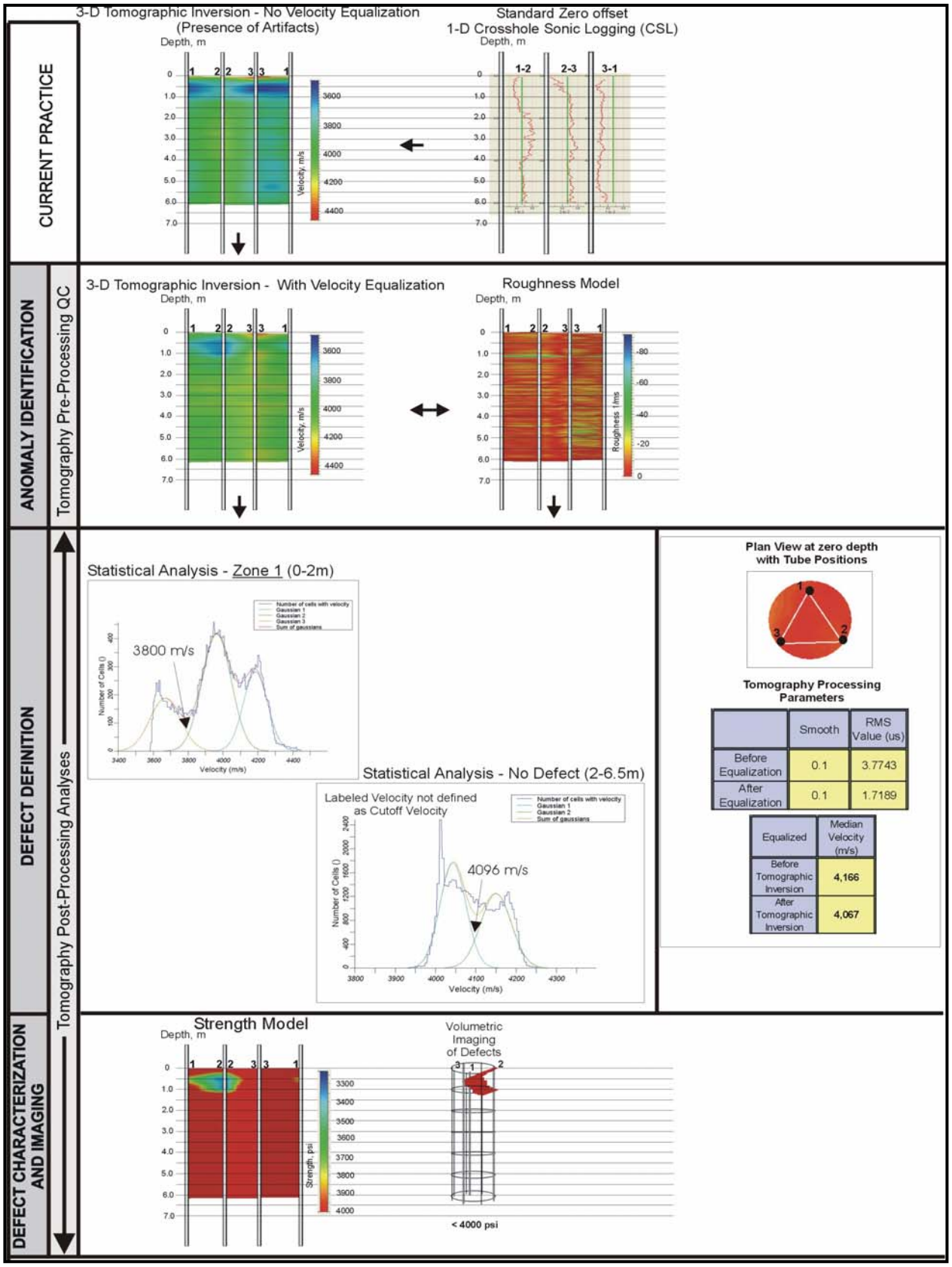

Figure 60. Schematic. Defect Characterization and Imaging Results from Shaft P4A, Jim Camp Bridge.

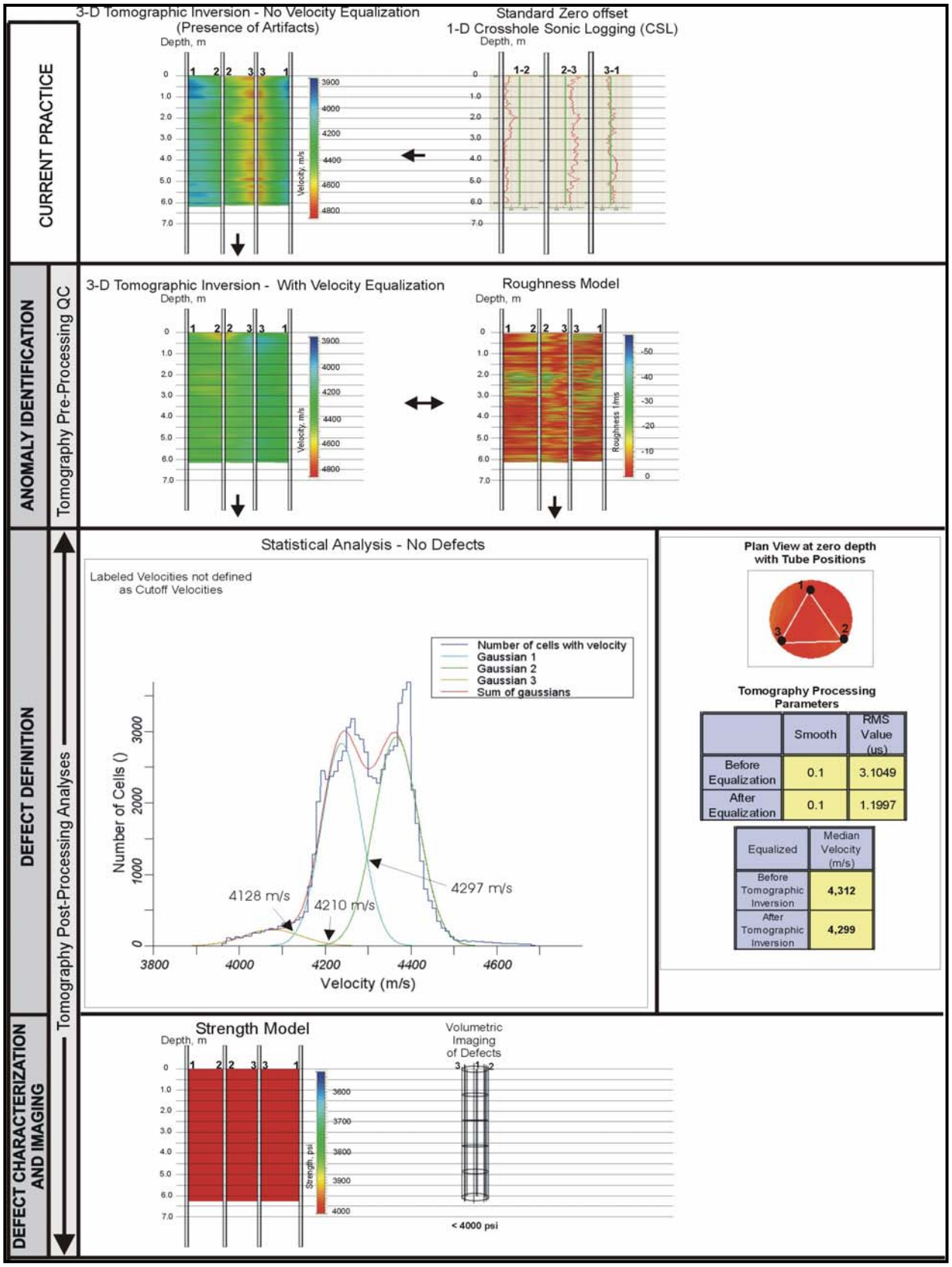

Figure 61. Schematic. Defect Characterization and Imaging Results from Shaft P4B, Jim Camp Bridge.

5.4 SEVENMILE-GOOSBERRY ROAD BRIDGE RESULTS

The Sevenmile-Gooseberry Road Project is located at Fishlake National Forest, near Salina, Utah. Six (6) existing shafts were tested using standard crosshole sonic logging by Olson engineering. Each drilled shaft had a diameter of 0.91 m (3 ft) and each contained three (3) 50.8 mm (2 in) I.D. schedule-40 steel access tubes.

In summary, CSL results indicated five (5) shafts out of a total of six (6) shafts to exhibit a soft bottom condition at the bottom 0.5 – 1 m (1-3 ft). The defective shafts were Abutment 2: Shafts 8, 9,10, 11, and 12. Subsequently, gamma-gamma density (GDL) and neutron-moisture logging (NML) was performed by Blackhawk GeoServices which confirmed the CSL soft bottoms for independent verification of anomalies. In addition, as reported in Section 4.1.3.1, laboratory ultrasonic pulse velocity (UPV) testing was performed at 4, 7, 14, 21, and 28 day intervals to obtain strength information.

Results from the Sevenmile-Gooseberry test site are summarized below:

5.4.1 Sevenmile-Gooseberry, Shaft 7 (Figure 62)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, is highly un-balanced, probably due to the tube positioning errors in the field.
2. *Anomaly Identification and Verification* – Zero-offset CSLT with velocity equalization indicates no anomalies. GDL data indicates no anomalies. (In our presentation format, GDL data is shown along with mean, 2, and 3 standard deviations from mean indicated in green, blue, and red vertical lines, respectively).
3. *Defect Definition* – No single low cut-off velocity can be determined for the sound shaft.
4. *Defect Characterization and Imaging* – No anomalies are detected in the shaft.

5.4.2 Sevenmile-Gooseberry, Shaft 8 (Figure 63)

1. *Current Practice* – Standard CSL indicates a soft bottom between 17-17.5 m.
   Zero-offset tomography (CSLT), with no velocity equalization, images the soft bottom.
2. *Anomaly Identification and Verification* – Zero-offset CSLT with velocity equalization better resolves the soft bottom with slight indication in the roughness model. GDL (shown in black) indicates no anomalies; therefore, the anomaly is located in the interior portion of the shaft. Note, however, that NML (shown in red) indicates that a high moisture zone exists in the bottom of the shaft.
3. *Defect Definition* – A single low cut-off velocity of 2,807 m/s is obtained for the whole shaft, which is less than the shaft median velocity (3,344 m/s).
4. *Defect Characterization and Imaging* – The soft bottom is clearly imaged in the strength model. Volumetric imaging indicates the soft bottom to be structurally significant (<16,500 kPa (2,400 psi)).

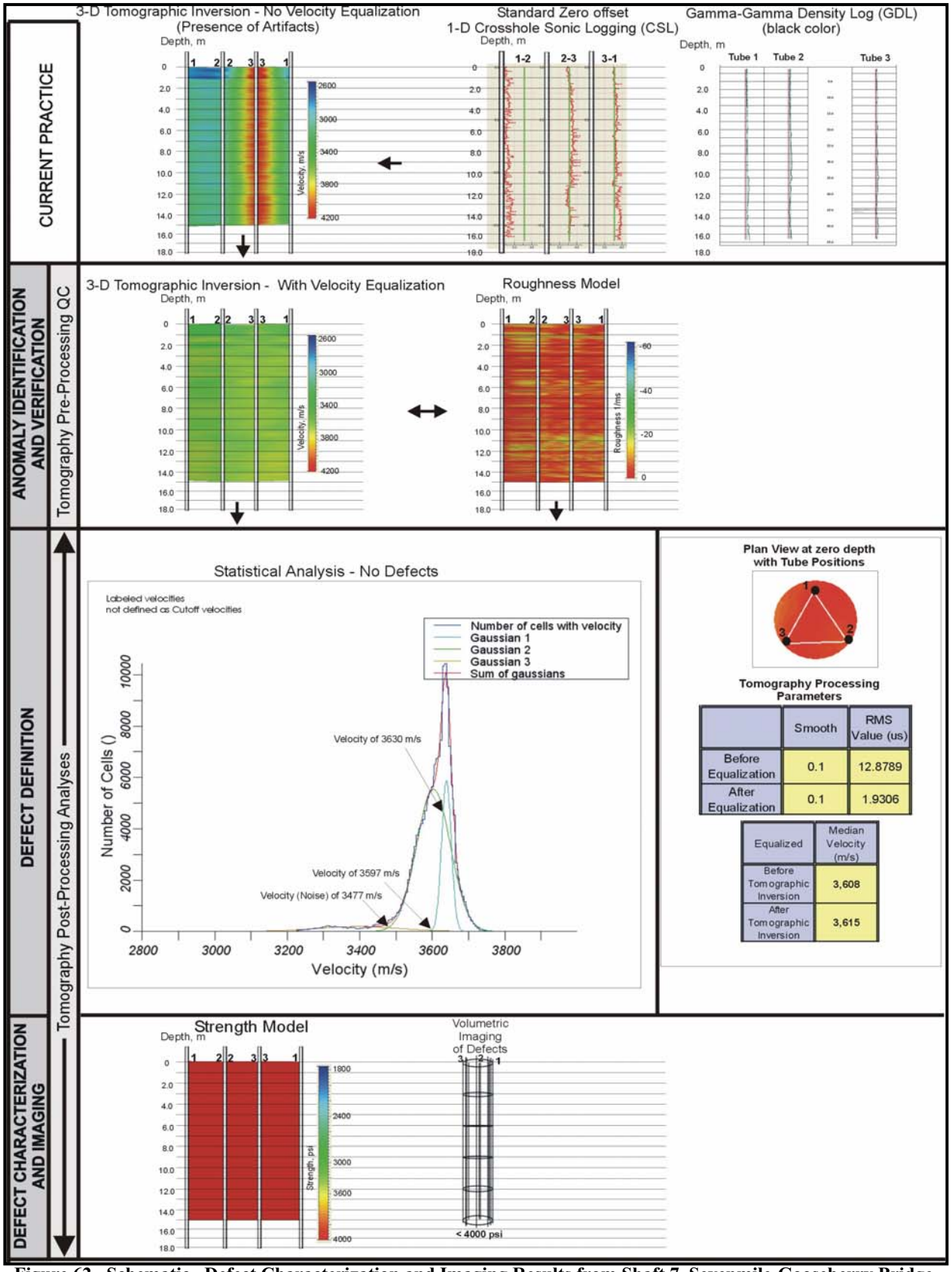

Figure 62. Schematic. Defect Characterization and Imaging Results from Shaft 7, Sevenmile-Gooseberry Bridge.

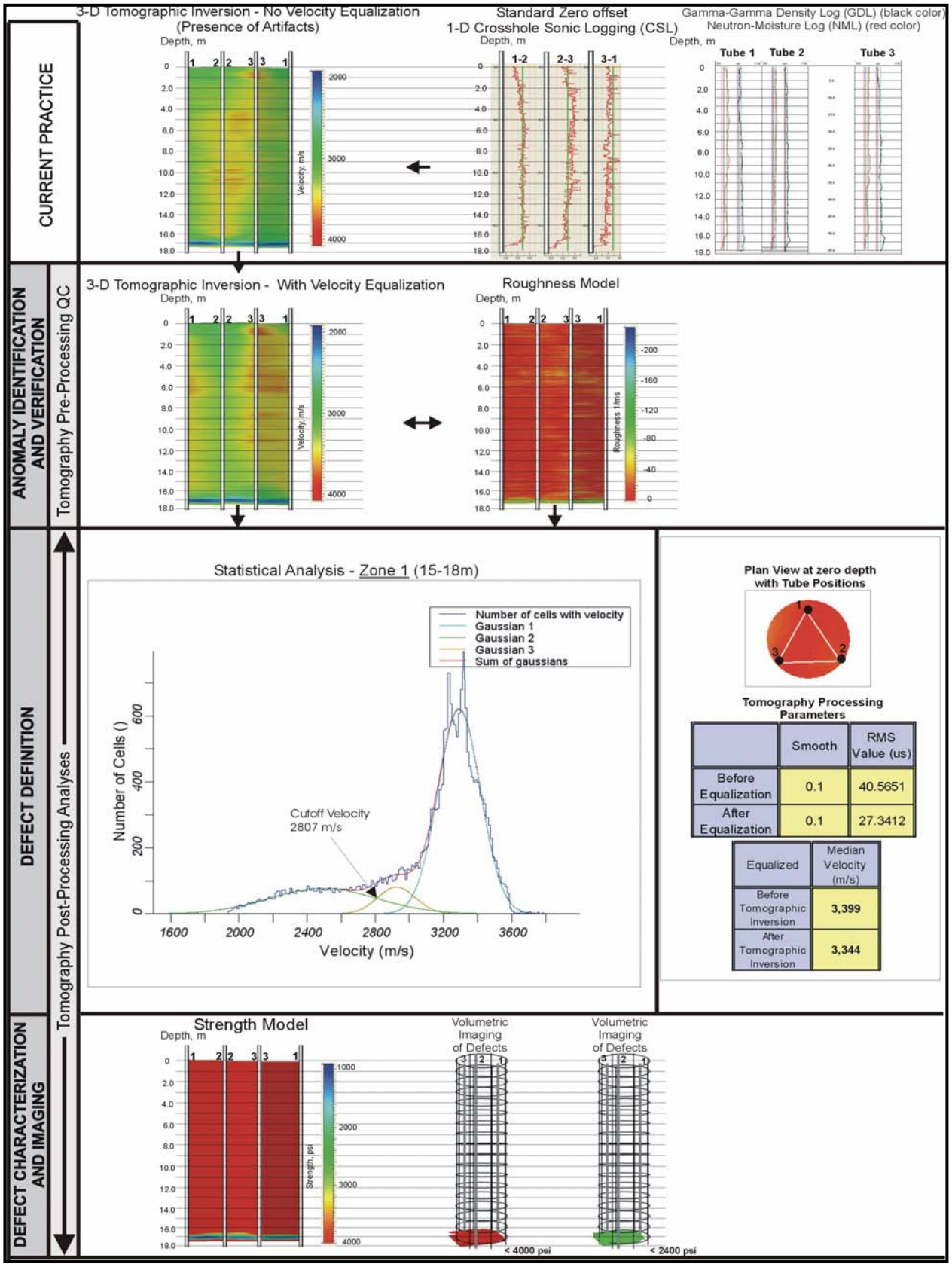

Figure 63. Schematic. Defect Characterization and Imaging Results from Shaft 8, Sevenmile-Gooseberry Bridge.

5.4.3 Sevenmile-Gooseberry, Shaft 9 (Figure 64)

1. *Current Practice* – Standard CSL indicates a soft bottom between 17-17.5 m. Zero-offset tomography (CSLT), with no velocity equalization, images the soft bottom.
2. *Anomaly Identification and Verification* – Zero-offset CSLT with velocity equalization slightly better resolves the soft bottom with slight indication in the roughness model. GDL (shown in black) and NML (shown in red) confirm the soft bottom anomaly.
3. *Defect Definition* – A single low cut-off velocity of 2,634 m/s is obtained for the whole shaft.
4. *Defect Characterization and Imaging* – The soft bottom is clearly imaged in the strength model. Volumetric imaging indicates the soft bottom to be structurally significant.

5.4.4 Sevenmile-Gooseberry, Shaft 10 (Figure 65)

1. *Current Practice* – Standard CSL indicates a soft bottom between 16-16.5 m near Tube 2. Zero-offset tomography (CSLT), with no velocity equalization, images the soft bottom.
2. *Anomaly Identification and Verification* – Zero-offset CSLT with velocity equalization better resolves the soft bottom with good indication in the roughness model. GDL indicates only a small drop in density in Tube 2; therefore, the anomaly is situated in the inside of the shaft just missing Tubes 1 and 3.
3. *Defect Definition* – A single low cut-off velocity of 3,455 m/s is obtained for the whole shaft.
4. *Defect Characterization and Imaging* – The soft bottom is clearly imaged in the strength model. Volumetric imaging indicates the soft bottom to be structurally significant (<16,500 kPa (2,400 psi)).

5.4.5 Sevenmile-Gooseberry, Shaft 11 (Figure 66)

1. *Current Practice* – Standard CSL indicates a soft bottom between 17-17.5 m. Zero-offset tomography (CSLT), with no velocity equalization, images the soft bottom.
2. *Anomaly Identification and Verification* – Zero-offset CSLT with velocity equalization better resolves the soft bottom with slight indication in the roughness model. GDL indicates an anomaly only in Tube 3; therefore, the anomaly extends to the interior portion of the shaft just missing Tubes 1 and 2.
3. *Defect Definition* – A single low cut-off velocity of 2,831 m/s is obtained for the whole shaft.
4. *Defect Characterization and Imaging* – The soft bottom is clearly imaged in the strength model. Volumetric imaging indicates the soft bottom to be structurally significant (<16,500 kPa (2,400 psi)).

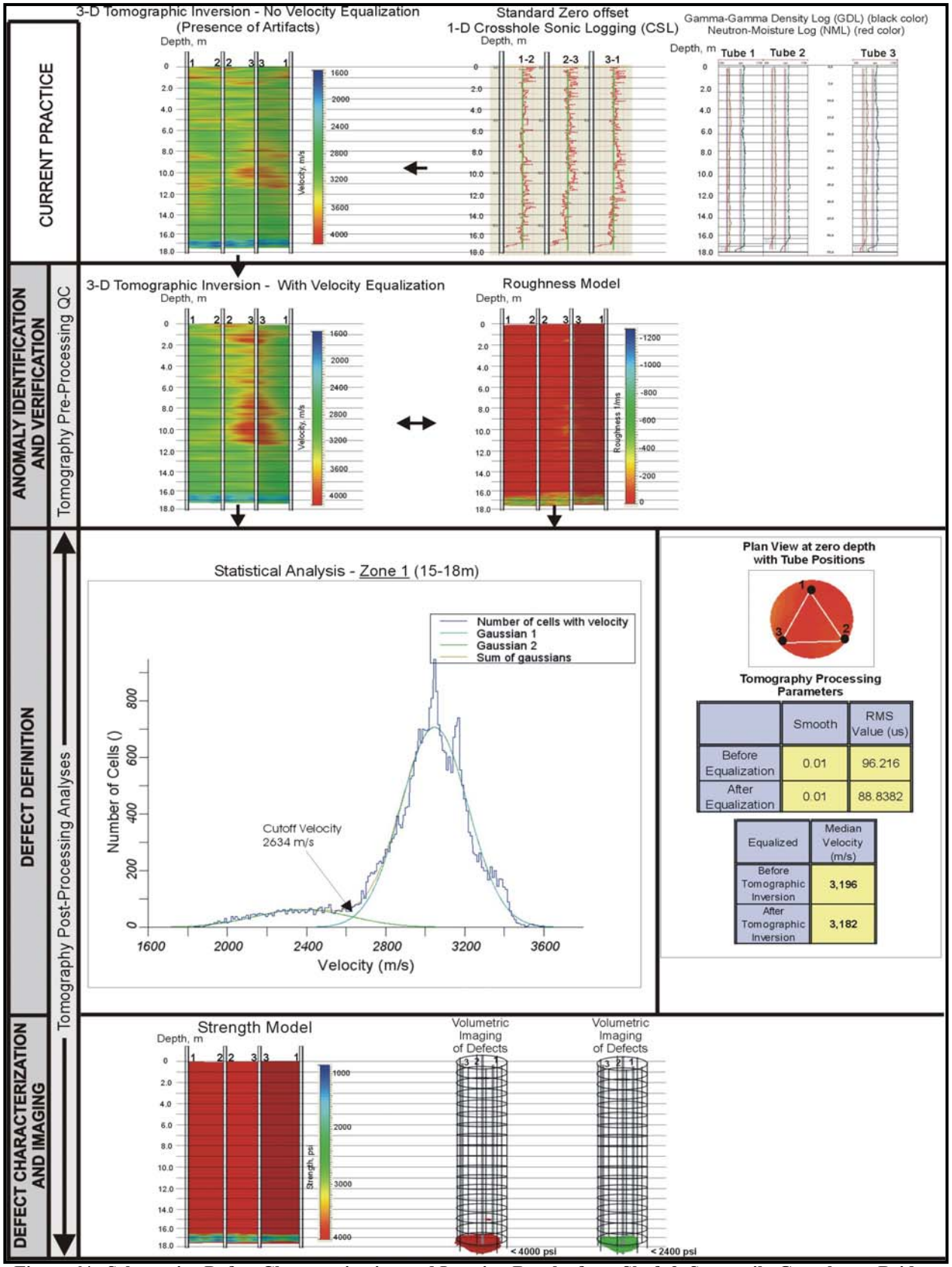

Figure 64. Schematic. Defect Characterization and Imaging Results from Shaft 9, Sevenmile-Gooseberry Bridge.

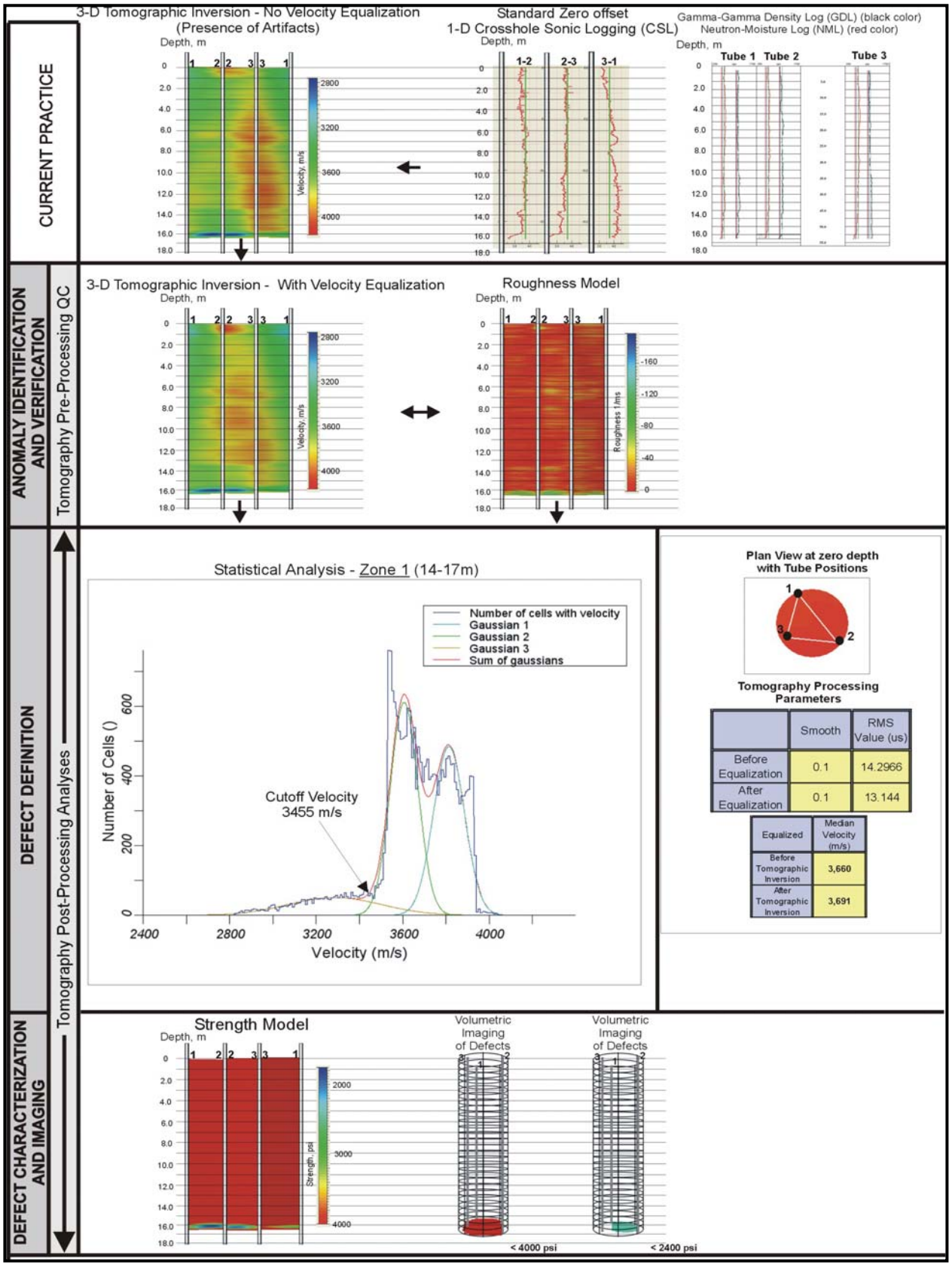

Figure 65. Schematic. Defect Characterization and Imaging Results from Shaft 10, Sevenmile-Gooseberry Bridge.

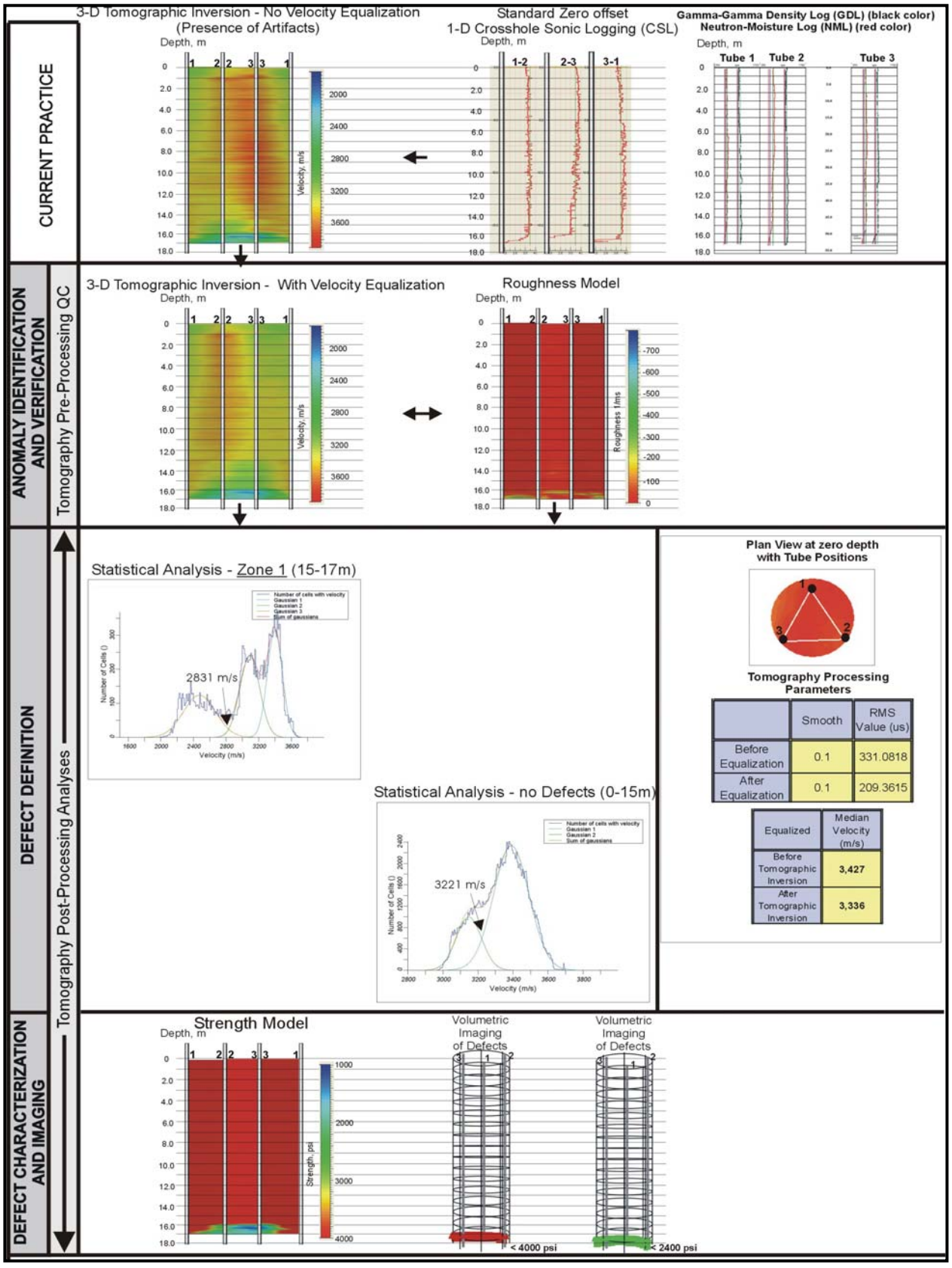

Figure 66. Schematic. Characterization and Imaging Results from Shaft 11, Sevenmile-Gooseberry Bridge.

5.4.6 Sevenmile-Gooseberry, Shaft 12 (Figure 67)

1. *Current Practice* – Standard CSL indicates no anomalies.
   Zero-offset tomography (CSLT), with no velocity equalization, is highly un-balanced, probably due to the tube positioning errors in the field.
2. *Anomaly Identification and Verification* – Zero-offset CSLT with velocity equalization indicates a small anomaly between 14-16 m. GDL also indicates no anomalies.
3. *Defect Definition* – A single low cut-off velocity of 2,596 m/s is obtained for the whole shaft.
4. *Defect Characterization and Imaging* – One small defect between 13-16 m near Tubes 2 and 3 is indicated. Volumetric images indicate that this defect is not structurally significant (>16,500 kPa (2,400 psi)).

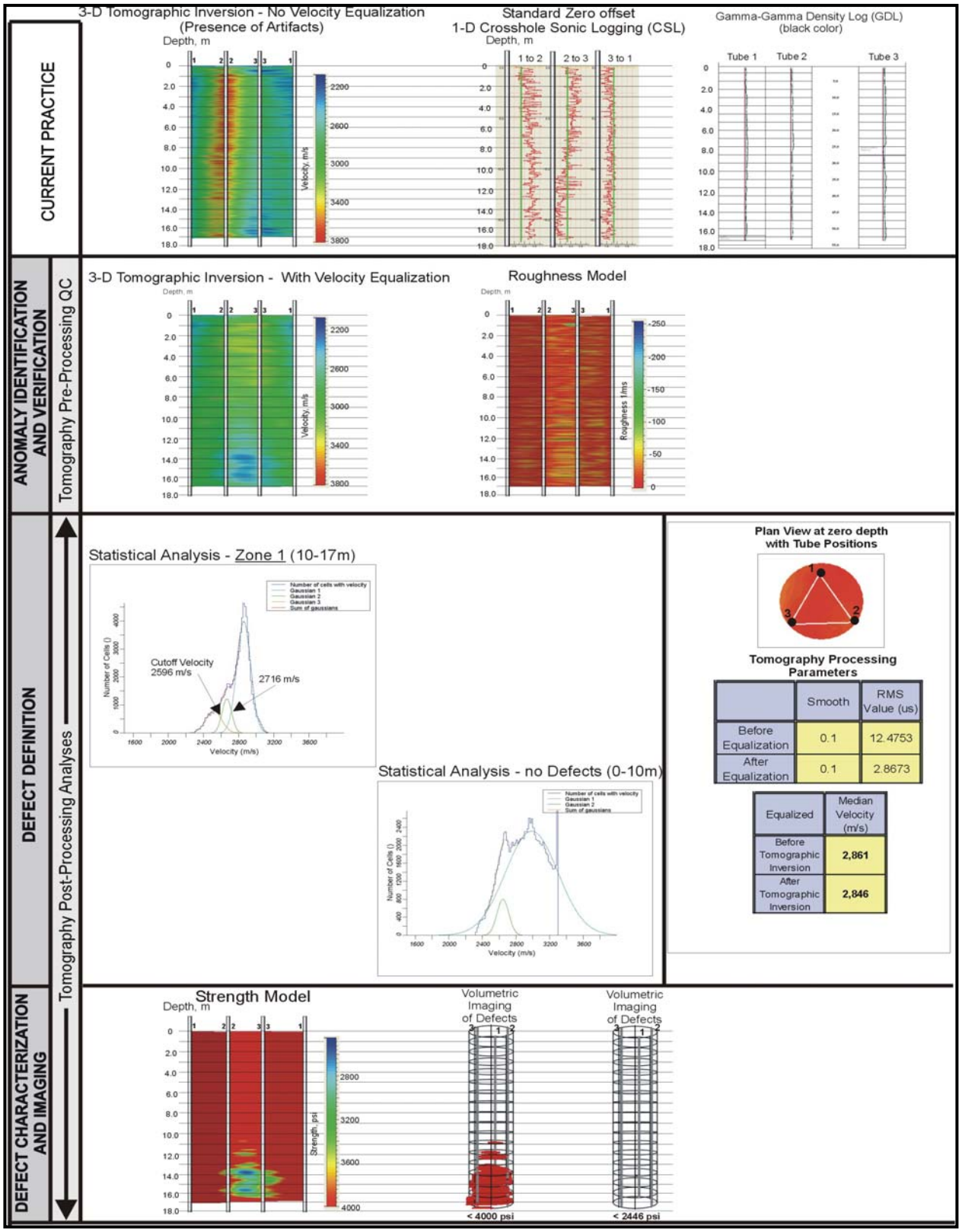

Figure 67. Schematic. Characterization and Imaging Results from Shaft 12, Sevenmile-Gooseberry Bridge.