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MEMORANDUM

To: Mike Pucherelli, Group Manager, Remote Sensing & Geographic Info. Group

From: Edmond W. Holroyd, III
Research Physical Scientist

Subject: Thermal infrared (FLIR) studies in the eastern Grand Canyon

Introduction

On 28 May 1994 helicopter flights were made in the eastern Grand Canyon in the morning and afternoon and along the Little Colorado River (LCR) in the morning. The instrumentation was a thermal infrared imaging camera (FLIR, forward-looking infrared) operated by a FLIR technician. B&W thermal images were recorded on one set of 3/4 inch video tapes. Normal color video images from a camera located inside the FLIR housing were recorded on a separate set of video tapes. The Colorado River (CR) was flown from about mile 16.5 to mile 78. The LCR was flown from the confluence with the CR (mile 0) to mile 18.

The thermal measurement system developed for the FLIR data was described in my memorandum to you dated 12 August 1994, with subject: FLIR temperature calibrations. A memorandum of 19 September 1994 had the subject: LCR video mosaic. Technical Memoranda No. 8260-95-01 had the title, Thermal infrared (FLIR) mosaics of the lower Little Colorado River and FLIR instrumentation. No. 8260-95-02 had the title, Video and thermal infrared (FLIR) mosaics for the Little Colorado River, Miles 13-18. No. 8260-95-03 had the title, Temperatures and warm springs along the Little Colorado River. All three were dated 1 March 1995. Those memoranda are companions to this report and present additional details and descriptions of the FLIR system that may not be fully covered here.

FLIR calibrations

The FLIR instrument was calibrated by flying over water bodies whose temperatures were being directly measured by instruments in the rivers. The calibration sites were near the CR and LCR confluence where contrasting water temperatures of 11.2 C represented the CR and 21.7 C represented the LCR at a 2 km upstream location. Temperatures from additional river sites were not useful in this study for reasons illustrated in this report.

The FLIR instrument produced artificial thermal gradients across the field of view. Some were mostly removed by equation. Others remain. They are the result of a thermal reference screen within the FLIR instrument being affected by the proximity of electronic heat sources. An even greater challenge was made by having uncalibrated gain and offset knobs on the control panel operated by the FLIR technician. These were adjusted during the third tape of the morning flight and throughout the afternoon flight. As a result, the initial morning tapes were at settings (medium to low gain) that gave grainy

initial morning tapes were at settings (medium to low gain) that gave grainy temperature patterns along the CR. After adjustment the CR thermal images (tape 3) had excellent thermal pattern definition but unknowable offset. The fourth tape of the morning covered a minor part of the CR and all of the LCR to mile 18. Its temperature patterns were excellent and fully calibrated. The afternoon flight produced three tapes of FLIR data of high contrast that saturated all of the higher backwater temperatures that we were trying to measure.

Table 2 in the memorandum of 12 August 1994 gives the calibration equations applicable to (#1) the morning CR data from miles 50 to 63.5, (#2) the morning CR data from miles 61 to 63 (upstream flight) and all LCR miles, and (#3) the afternoon CR data from miles 52 to 65.5. There were obvious offset changes for data at other river miles which had no temperature calibrations available.

In an attempt to salvage the good thermal image data from CR tape 3 on the morning flight, it was assumed that the gain for miles after 63.5 was the same as for the LCR tape (4). A simple offset was made by subtracting 0.6 C from the calibration equation #2 results, or a digital number of 6 from equation #2. That gave CR temperatures in the expected range.

Temperature calibration sites

The river temperatures at the measurement sites were previously presented in Table 1 of the memorandum of 12 August 1994. The thermometer locations were never precisely measured, such as to the nearest meter. Since then some site identification errors were changed. The location precision was still insufficient for temperature calibrations in the presence of strong gradients. A revised Table 1 is presented here:

Table 1. River water temperature revised calibrations

Locations and types	Flight times (GMT) and temperatures, deg.C				
rm 58.8L backwater	141257,		12.9	005654,	22.4
rm 59.2L backwater	141333,	141534,	13.1	005719,	21.1
rm 60.7L backwater	141645,		none	005810,	18.7
rm 62.6R backwater	141816,	143746,	11.2	005929,	12.1
rm 63.7R backwater	141913,		12.7	010020,	22.4
rm 64.6R return channel	142005,		11.2	010106, 010348,	12.4
rm 65.3L return channel	142037,		12.5	010135, 010417,	12.6
rm 65.3L isolated pool	142037,		none	010135, 010417,	26.3
CR upstream of confluence	1414 ,		11.2		
about 2 km up LCR	1440 ,		21.7		

Figures 1 to 7 show the video (left) and raw FLIR (center) views of each calibration site and the derived temperature patterns (right) using the equations already mentioned. Every site had two or three remote examinations during the day. All images are oriented to downstream at the top, with left and right in agreement with normal river notation. Only one view, from morning tape 4, flown upstream, had to be reoriented. Hours of 07 in the legends and 14 in the images are local time and GMT, respectively in the early morning. Hours of 17, 18, and 00, 01 are likewise local time and GMT in the late afternoon.

Figure 1 shows a backwater on the left side. In the video views it is the

dark zone between the shore and the sandbar. The morning temperature image is too grainy to identify the thermometer site which was reading 12.9 C. In the afternoon the thermal image was too saturated (at 12.2 C) to show the thermometer site which was then reading 22.4 C. The afternoon raw FLIR shows the warmer backwater weakly at the left side of the image, indicating that most of the backwater was near the cold river water temperature. The site of the much warmer thermometer measurements cannot be determined with this data.

Figure 2 shows a backwater on the left side. In the upper left video it is the darker water between the shore and sandbar slightly below the center of view. Values near 13.1 C are present in the temperature image, but the shoreline gradient is so strong that any backwater cannot be seen. In the afternoon the image is saturated at 12.2 C, so the 21.1 C of the backwater cannot be seen. The FLIR temperature data for this warm backwater are thereby useless on this date because of operational deficiencies.

Figure 3 shows a backwater on the left side as the dark water in the middle of the video image. The thermometer was not operating during the morning flight times. The grainy temperature patterns indicate some patterns in the backwater in the upper left. The afternoon temperature of 18.7 C was overpowered by the saturation at 12.2 C. The raw FLIR image shows that there is a temperature pattern in this small backwater, most of which was not recorded.

Figure 4 shows a small backwater on the right side. It is the dark patch in the center of the lower left video image. The first morning pass shows a grainy temperature pattern. The second morning pass was made using equation #2 settings, giving an excellent and calibrated thermal image. Unfortunately, the backwater was at the same temperature as the river. In the afternoon the thermometer warmed to 12.1 C, just barely less than the 12.2 C saturation value. Such values do appear in the image, but it is not known if the thermometer was at such locations. The shoreline temperature gradient appears to be large. So this site was not much help for temperature calibrations except for giving the main river temperature for an offset value.

Figure 5 shows a rectangular bay on the right. The backwater temperature measurement was indicated to be at its upper right corner. The morning temperature was 12.7 C and the afternoon was 22.4 C, much greater than the 12.2 C saturation temperature. The morning temperature image was from the data salvaged by subtracting 0.6 C. Values near 12.7 C do appear in that image but are lost in the shoreline gradient. Therefore the FLIR could not be calibrated from these values.

Figure 6 shows a tiny return channel to the right of the boulder at the center right side of the river. The morning temperature was 11.2 C, the same as the river. The afternoon temperature was 12.4 C, just above the saturation temperature of 12.2 C. These measurements were not useful for FLIR calibrations. Therefore the morning calibration had to use the 0.6 C offset. There appeared to be no significant warming in this small return channel because it is too small.

Figure 7 shows the sites of temperature measurements at a side channel and an isolated pool on the left side. The location of the return channel is not obvious in any of the images. Its temperatures of 12.5 C and 12.6 C suggest that it was dominated by the cold river water. The isolated pool is not visible in the video views. It is a bright patch in the morning raw FLIR

area of about 10 x 25 meters in the CR before it vanishes by mixing. Such warmer water should be expected to float on top of the cold CR water. Looking back at full scene temperature image, it is seen that the thermal influence of Vasey's Paradise water is insignificant in the Colorado River. Only an area within 10 meters of the shore is about 3 C warmer.

Basalt Canyon side channel Throughout the study area the side channels around islands have the same temperatures as the main flow of the Colorado River, according the FLIR data. Similarly, all embayments have the same river water temperature. Most backwaters were not sufficiently sheltered to have warmer water in the morning. In the afternoon the FLIR was so saturated that warm backwaters could not be observed.

Only one site appeared to have water shallow enough to restrict flow and thereby enable a warming of the water. That was at Basalt Canyon, at about mile 69.3 right. The helicopter pilot tried to follow the main river there on both the morning and afternoon flights, and so he missed most of the side channel flow. The return flow was, however, imaged but its warming was only slight.

Two orthophoto maps were spliced to form a registration basemap for mosaics of the images. The video frames were registered to the basemap by common landmarks of vegetation and debris patterns. The frames were individually warped to a 0.5 meter resolution image in the Arizona State Plane coordinate system using the MIPS plane projective method. That results in trapezoids that remove distortions from the off-nadir viewing caused by the direction changes of the helicopter. Frames that warped to rectangles indicate that the view was close to nadir. The FLIR images were registered to the simultaneous video views and then checked against the basemap before warping.

Figure 9 shows the video mosaic for the morning view with the orthophoto map as a slightly darker background. Top is north and the river flows from top to bottom. The side channel pattern is on the left side of the figure, the right side of the river. It is apparent that most of the interesting area was missed. The main side channel flows the greater distance to an area of return flow. There is a minor side channel that takes a short cut back to the river. It appears that the minor side channel had no flowing water during the afternoon flight because of the lowering river flow. Near zero flow is also suspected for the morning view.

Figure 10 shows the morning temperature mosaic. The orthophoto map was used as a background. Its visual gray scale was assigned the colorized temperatures which are obviously false. This was done to show the locations of the side channels that were not imaged by the FLIR. It is obvious what is the bluish background image and what is the temperature mosaic.

A close examination of individual frames of the FLIR data show that the far right side of the image (left in the figure) has enhanced temperatures because of temperature reference gradients inside the FLIR instrument. The indicated river temperature is therefore not uniform at mile 69, the bend at the upper left. The light blue should have extended to the west side of the bend and into the side channel. Similarly, the temperatures at the return flows are abnormally increased. Therefore the amount of warming of the water while in the side channel cannot be determined with this FLIR data set.

image. That patch becomes green in the lower left part of the temperature image (upper right part of figure) and is annotated with a black arrowhead. Unfortunately, the pool temperature was not being measured at the time of the morning flight. Using the 0.6 C offset adjustment, the FLIR indicates a value near 17 C. In the afternoon the thermometer indicated 26.3 C, but the FLIR was saturated at 12.2 C. Otherwise this might have been an interesting site for showing the value of FLIR determinations of temperature patterns.

Calibration discussions

None of the images in Figures 1 to 7 show useful calibrations. Either the FLIR settings were not the best (most common), the thermometers were not yet operating, the water was at the same temperature as the CR, or the shoreline thermal gradient was too strong to show the thermometer location. The FLIR can only look at the top fraction of a millimeter of the water surface. The thermometers were all resting on the bottom in both the rivers and backwaters. In the afternoon they were probably affected strongly by solar radiational warming of the river bottom during the day. I suspect that there was a strong vertical temperature gradient, unstable in the sense of having a thin film of warm water next to the soil and rocks and cold river water immediately above. The thermometers were most likely within this gradient and did not measure the water temperatures that the FLIR was seeing at the top of the water surface.

Significant temperature patterns

Confluence mixing The warm water from the LCR mixes rapidly with the cold CR water at the confluence so that there is almost no trace of the LCR thermal pattern beyond the island. The Figures 2, 3, and especially 4 of the 12 August 1994 memorandum showed the various stages of mixing. The LCR water remains intact for about 1/4 of the way around the north side of the island. It then forks and has a temperature drop of about 8 C. Its swath is a little wider over the northern shore of the island. At the northwest edge of the island all of the warm water separates from the shore and travels to the middle of the Colorado River as it passes over a small rapid and nearly vanishes. Beyond that a trace of warmth of about 0.2 C temperature difference can be seen in a large eddy on the west-northwest side of the island. The eddy can best be seen in the raw FLIR image mosaic of Figure 4b of that memorandum. The LCR flow was only a trace of the much larger CR flow and so its thermal influence vanished rapidly.

Vasey's Paradise A waterfall comes out of a spring in the limestone at Vasey's paradise, mile 31.8. Flowing from an underground source, it is expected that the water temperature would be different from the Colorado River. The morning images were examined to detect such differences, using calibration equation #1. There is some risk in using that equation because the FLIR instrument drifts with time and there are no nearby thermometer calibrations.

Figure 8 shows the red part of the video and calibrated temperature views of Vasey's Paradise. The location of the waterfall (white lines) above an abundance of dark vegetation is shown by an arrow in the B&W video view. The FLIR calibration indicates a CR temperature of about 7 C. The inset in the lower right shows an enlargement of the area where the water from the waterfall enters the CR. The white line shows the visible shoreline. A land area below the waterfall has a temperature of 13.5 C. The spring water affects an

Figure 11 shows the afternoon temperature mosaic on the same false color background. The saturation of the FLIR instrument limits the observed temperatures to 12.2 C. The helicopter was far enough westward to reduce the false temperatures on the far right side of the images (left side of the figure). Even so, the light blue pattern in the first third of the side channel may be elevated by a few tenths of a degree. The return flow is nearer the center of the individual frames and thereby has more accurate temperature measurements. It appears that the return flow has a shading step of only one or two increments above the river temperature, amounting to 0.2 or 0.4 degrees of warming while in the side channel.

The minor side channel in Figure 10 has an obvious warming. It may not even have flowing water but merely wet sand caused by the lowering of the river flow. In Figure 11 there is little hint of cool temperatures in the minor side channel. It is almost fully saturated at temperatures of $\leq$12.2 C.

It appears that on future flights the pilot will need to be guided to depart from the river center line where there are important backwaters and side channels that might otherwise be out of the field of view. Having a video monitor available to the pilot will help his navigation.

Conclusions

This initial FLIR mission was exploratory, to test the applicability of the FLIR for monitoring temperature patterns in the Grand Canyon. The other memoranda showed that the FLIR obtained excellent data in the Little Colorado River canyon, mapping the temperature patterns in great detail and showing the locations of warm springs to mile 18 above the confluence.

The mappings in the Colorado River were not as useful. The main problem was that the gain and offset controls of the FLIR instrument were not at optimum settings for most of the flights. An attempt had been made to make them cover the range of temperatures seen at the CR and LCR confluence and apply those settings to the entire flight. However, sunlight confused the instrument during this initial set up by warming soil and rocks within the view of the instrument. The first two tapes in the morning and part of the third had settings that covered the desired temperature range but at coarse resolution. The upper and lower recorded temperatures were in great excess of the expected range of water temperatures. That resulted in grainy temperature images. The end of the third tape had a much better gain but no useful temperature monitoring sites were flown over so that the images could be properly calibrated. Tape 4 had the excellent LCR settings and imaged only two miles below the confluence, including one monitoring site. In the afternoon the gain was very high, causing a saturation of temperatures only slightly above the river temperature. Therefore warm backwaters could not be measured; they were warmer than the saturation temperatures. Furthermore, assuming the Colorado River temperature to be only slowly increasing, there were obvious offset changes during the afternoon flight. That invalidated all settings away from the temperature monitoring sites.

The temperature measurements in the river need to be improved in the future. The instruments measured bottom temperatures and were probably strongly affected by river bed material heated by the sun. The FLIR measures the temperature of only the top fraction of a millimeter of the water. In well-mixed waters with much turbulence it is permissible to measure the tempera-

tures below the surface, but not at the bottom where there may be a strong thermal gradient. Thermometers attached to tethered buoys will be better for future measurements so that surface temperatures, not bottom temperatures, can be monitored.

It was found that few backwaters and no embayments had temperatures warmer than the river temperatures. Unlike the Green River near Island Park, the Grand Canyon backwaters and side channels may not be far enough from the main river to show appreciable warming. During the morning flight the backwaters and side channels had neither the solar energy nor the time to adjust to different temperatures because of the rapidly falling river flow. During the afternoon the flow had stabilized and solar energy had at least heated the river bottoms where the thermometers laid. It was the FLIR saturation in the afternoon which made the warm waters unobservable.

The FLIR instrument needs to have its gain and offset controls calibrated by laboratory tests before the next usage. Then the settings can be set for the expected range of temperatures, allowing a little excess at the cold and warm ends of that range. Those settings must not be changed in flight. Repeated passes over temperature monitoring sites in the river are needed to correct for FLIR instrumental drift with time, most severe during the first half hour of warmup.

As a final summary of the major points of this series of memoranda, I reiterate the following:

1) The FLIR instrument is appropriate for measuring thermal differences in the waters and adjacent land areas of the Grand Canyon area. As flown it had better than 0.5 m horizontal resolution and 0.2 C temperature resolution. It can properly map temperature patterns (if they exist) in backwaters. It can find warm (or cool) springs. It can map areas of high water table by evaporative cooling of wet sand in the hours before sunshine heats the land surfaces.

2) The FLIR instrument needs to be properly adjusted before flight to eliminate such technical problems as video camera color balance and FLIR image sync signal strength. It needs to have its gain and offset controls calibrated with bench tests. The controls need to be set and fixed before the flight for the expected range of temperatures. Changes in the settings during the flight are to be strongly discouraged.

3) The FLIR instrument needs to record water calibration images (independently measured by thermometers in water without thermal gradients) at the beginning, middle, and end of a flight to overcome the known drift. The drift is greatest during the first half hour of operation, so the instrument should be operated (but not recorded) during the travel time to the area of interest. The instrument should not be turned off until the end of all recordings.

4) An electronic indicator would be helpful to show that the FLIR is indeed pointed at nadir. The changing angle of attack of the aircraft makes it inappropriate to use the airframe as a reference for the horizontal. Off-nadir images require tedious georeferencing and warping if correct mapping of temperature patterns is desired.

5) There needs to be better deployment of thermometers in the water. The well-mixed Colorado River serves well as a cold calibration point. The well-

mixed portions of the LCR serve well as a warm calibration point. Therefore confluence area thermometers are most useful. An upstream CR calibration closer to Lees Ferry could supply an even colder reference. Thermometers should not be deployed at the bottom of the water because of solar heating gradients. Most CR backwaters are not sufficiently separated from the main CR to be useful calibration points for warmer temperatures. Deployment in areas of thermal gradients should be avoided. That will also eliminate the need for carefully surveyed thermometer locations.

PEER REVIEW DOCUMENTATION

PROJECT AND DOCUMENT INFORMATION

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REVIEW REQUIREMENT

Part A: Document Does Not Require Peer Review

Explain _____

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Peer Review restricted to the following Items/Section(s): Reviewer:

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REVIEW CERTIFICATION

Peer Reviewer - I have reviewed the assigned Items/Section(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer: David Eckhardt Review Date: 5-31-95
Signature

Reviewer: _____ Review Date: _____
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Preparer - I have discussed the above document and review requirements with the Peer Reviewer and believe that this review is completed, and that the document will meet the requirements of the project.

Team Member: Edmond W Holroyd III **Date:** 1 June 95
Signature

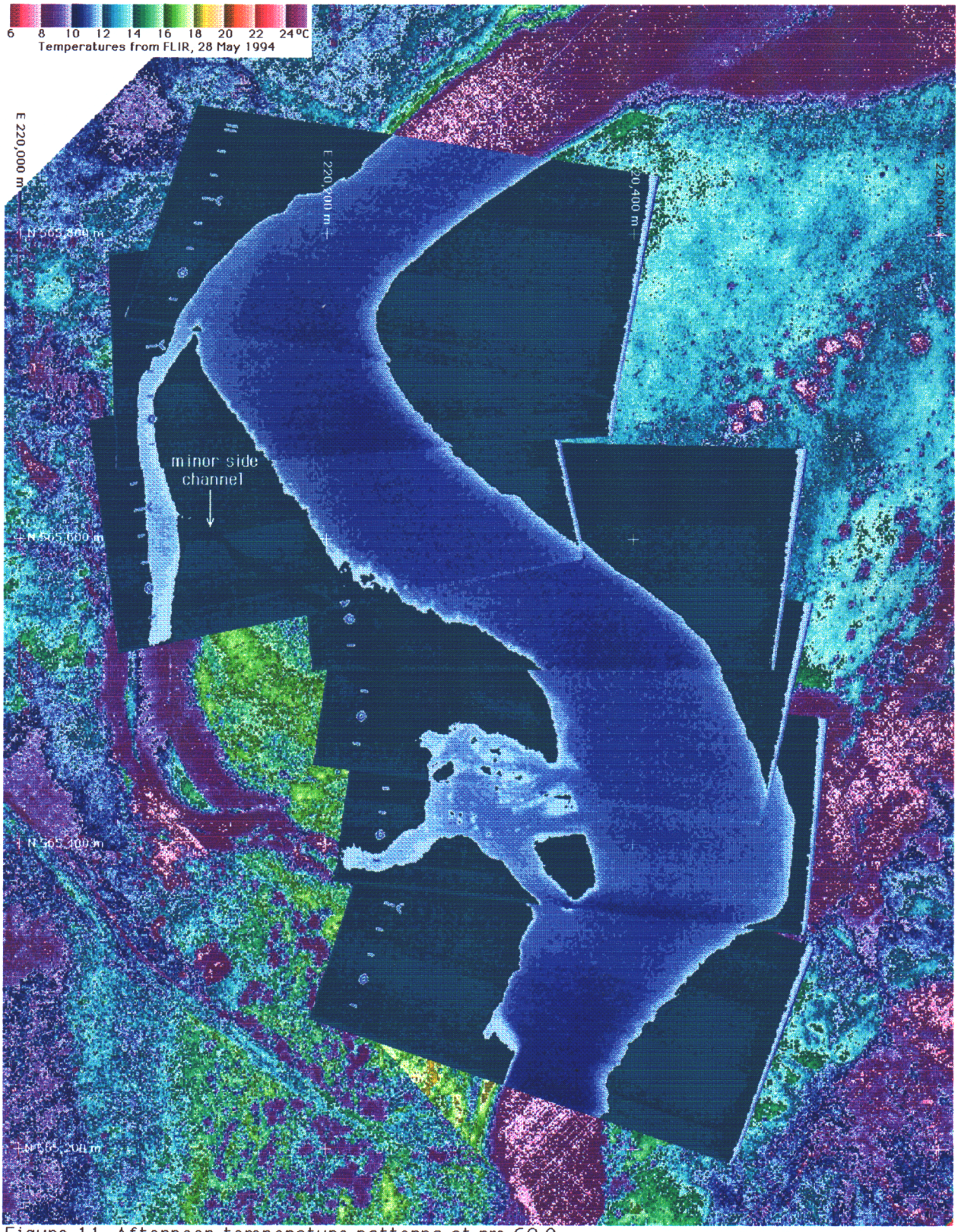

Figure 11. Afternoon temperature patterns at rm 69.0.

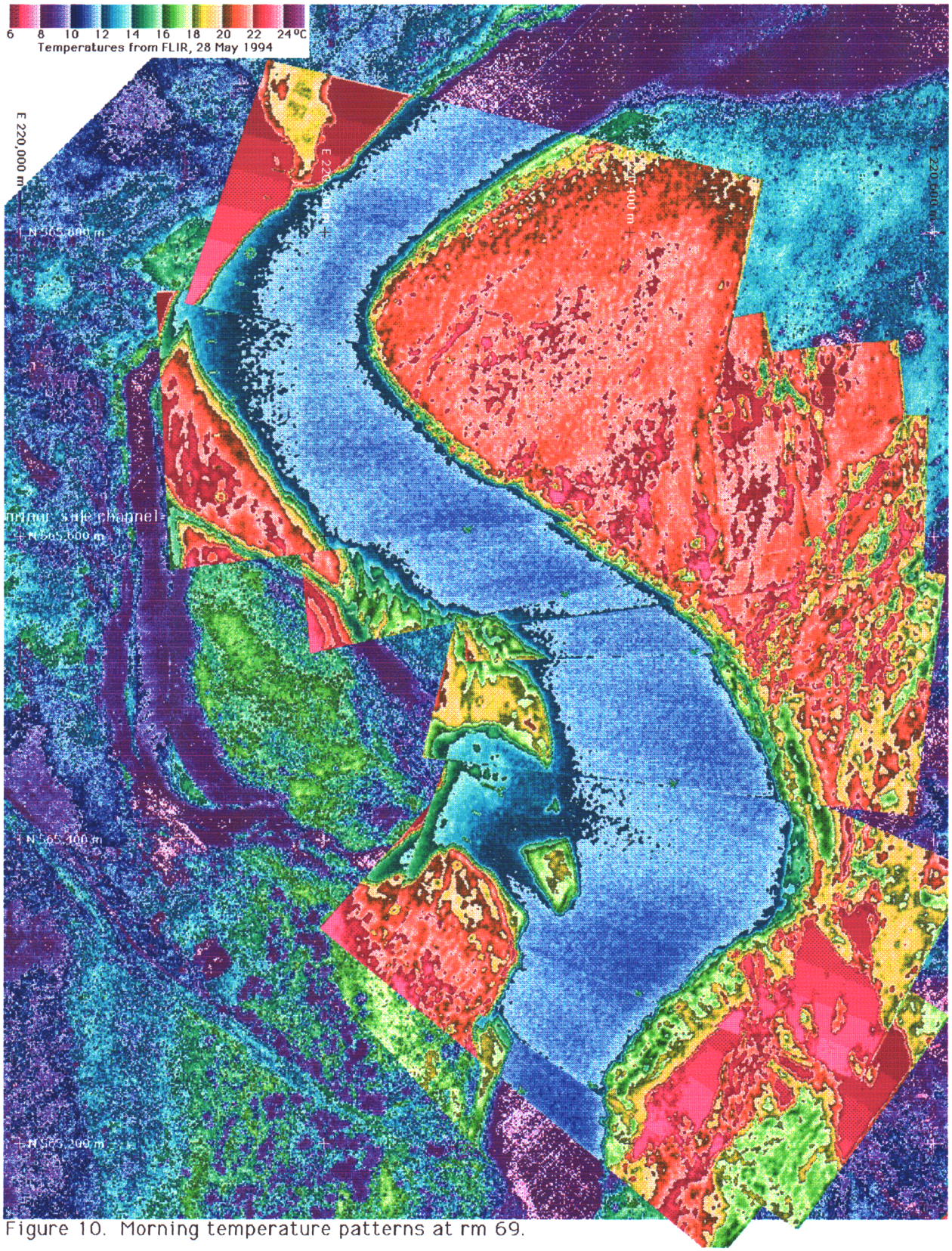

Figure 10. Morning temperature patterns at rm 69.

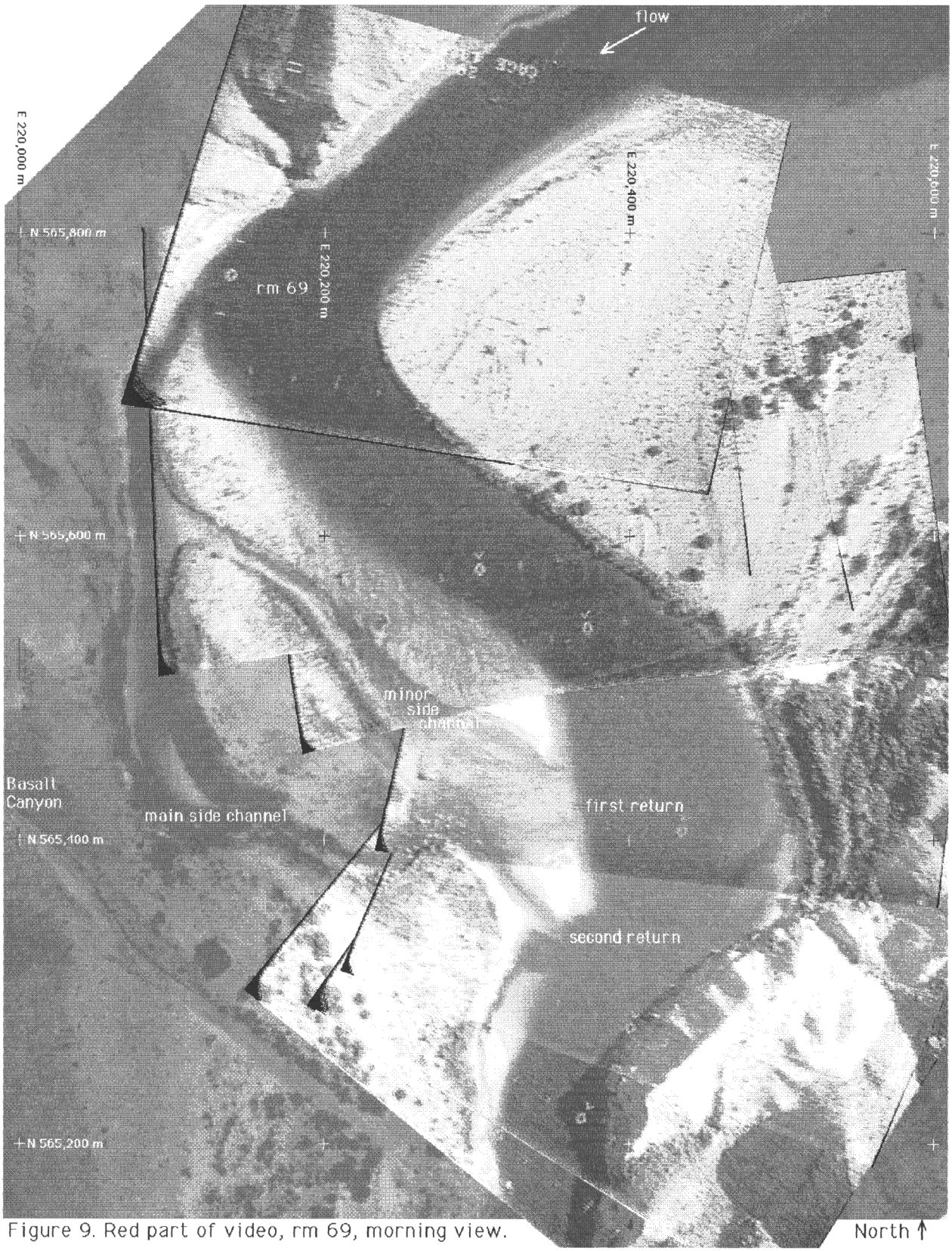

Figure 9. Red part of video, rm 69, morning view.

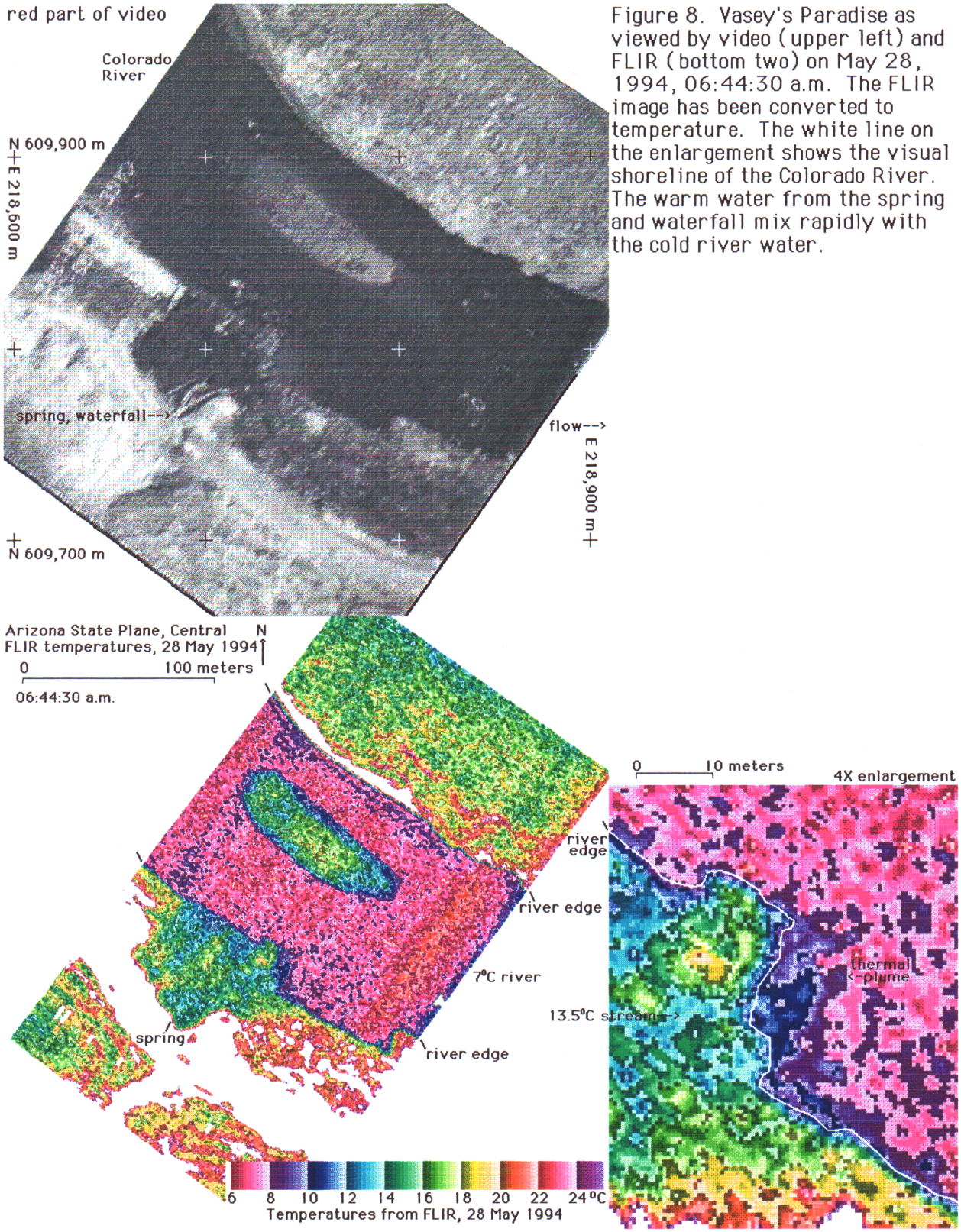

Figure 8. Vasey's Paradise as viewed by video (upper left) and FLIR (bottom two) on May 28, 1994, 06:44:30 a.m. The FLIR image has been converted to temperature. The white line on the enlargement shows the visual shoreline of the Colorado River. The warm water from the spring and waterfall mix rapidly with the cold river water.

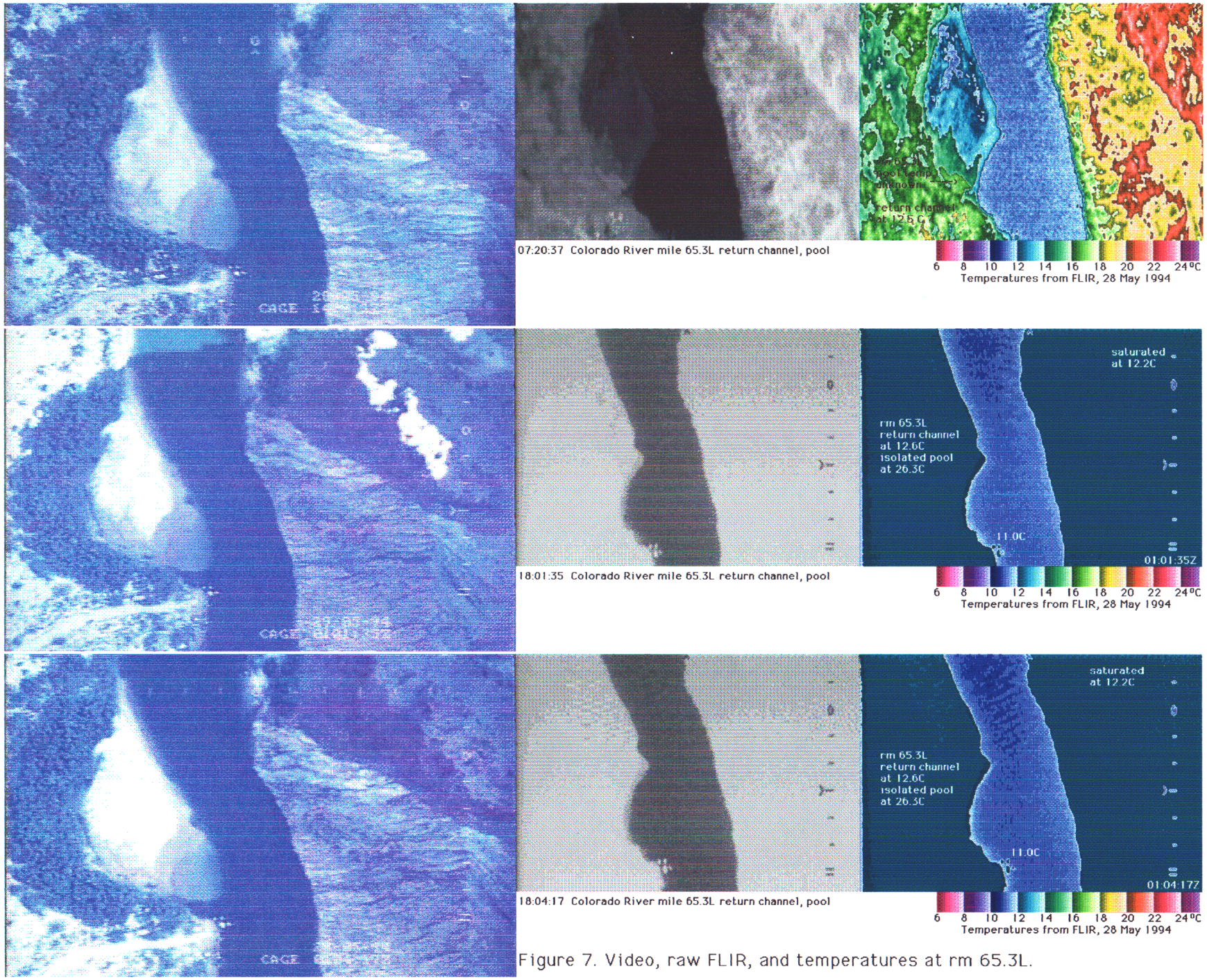

Figure 7. Video, raw FLIR, and temperatures at rm 65.3L.

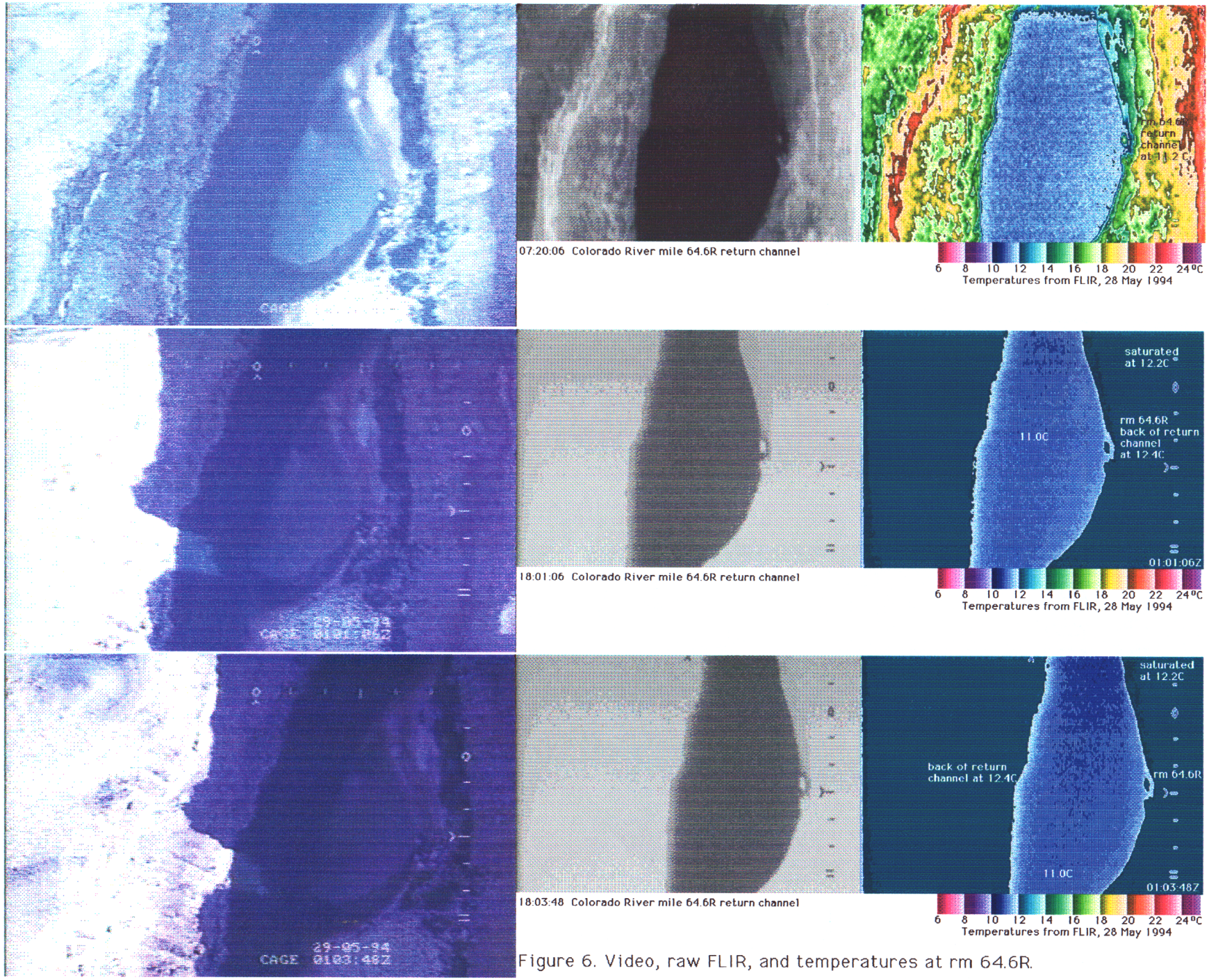

Figure 6. Video, raw FLIR, and temperatures at rm 64.6R.

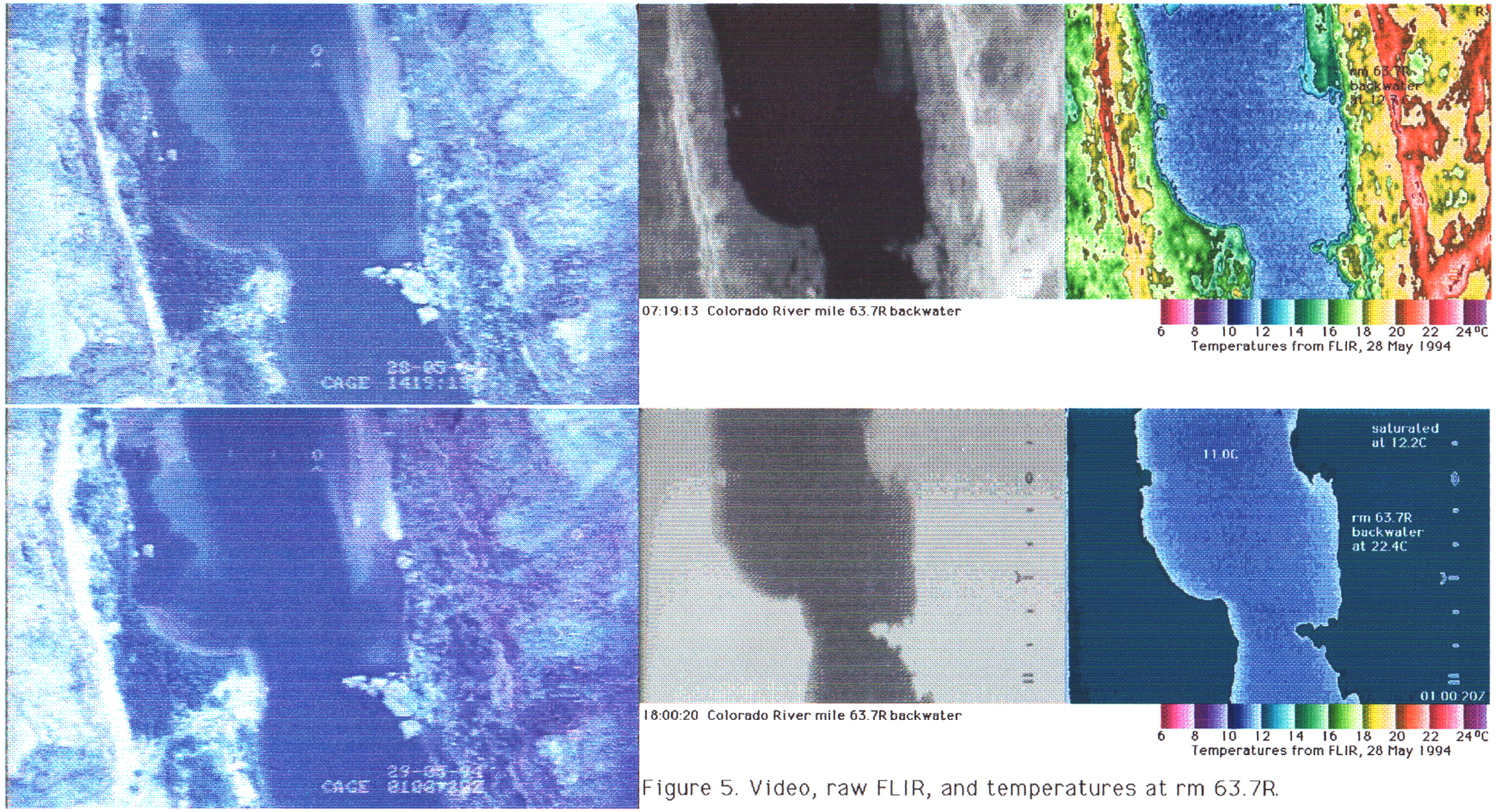

Figure 5. Video, raw FLIR, and temperatures at rm 63.7R.

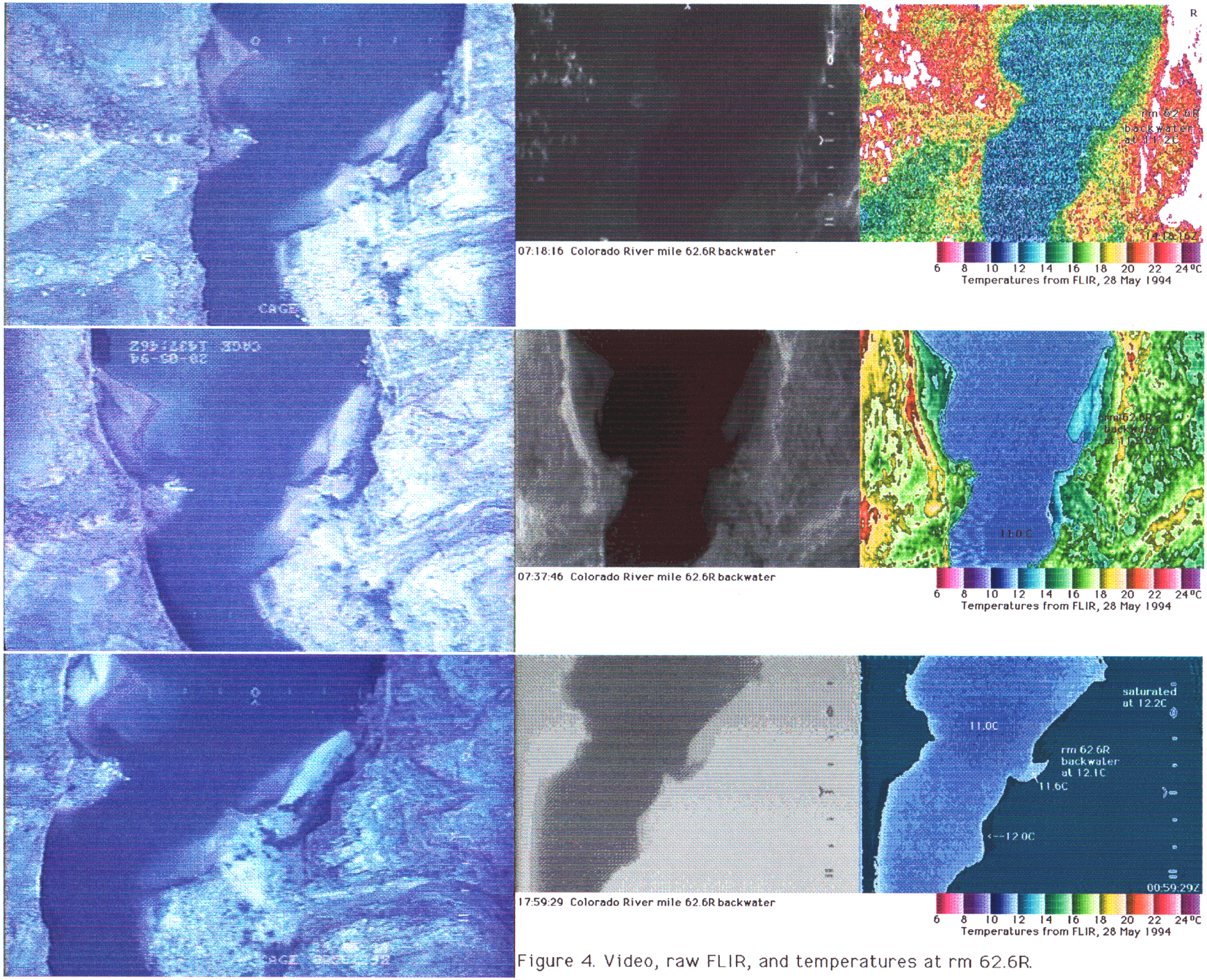

Figure 4. Video, raw FLIR, and temperatures at rm 62.6R.

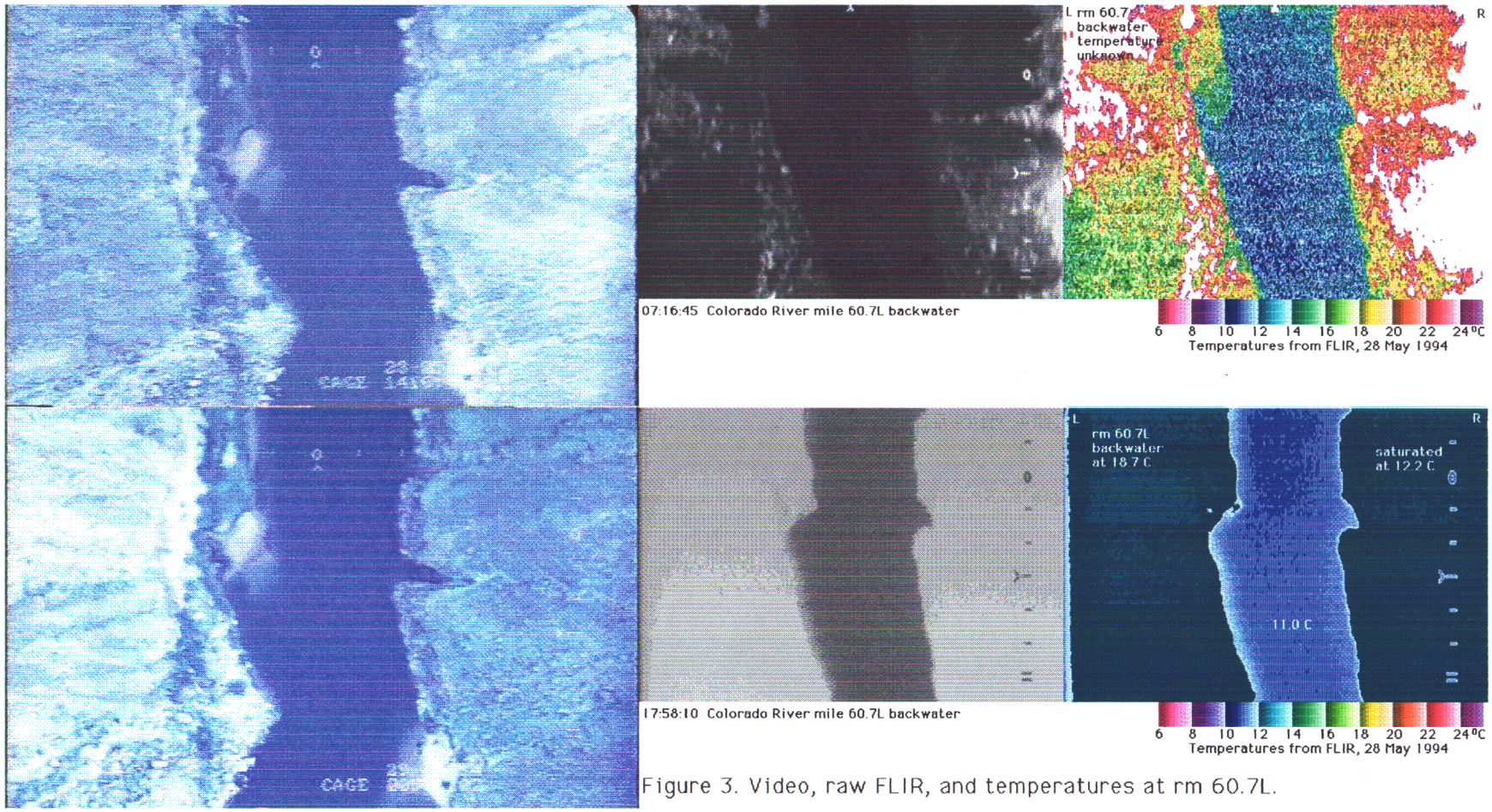

Figure 3. Video, raw FLIR, and temperatures at rm 60.7L.

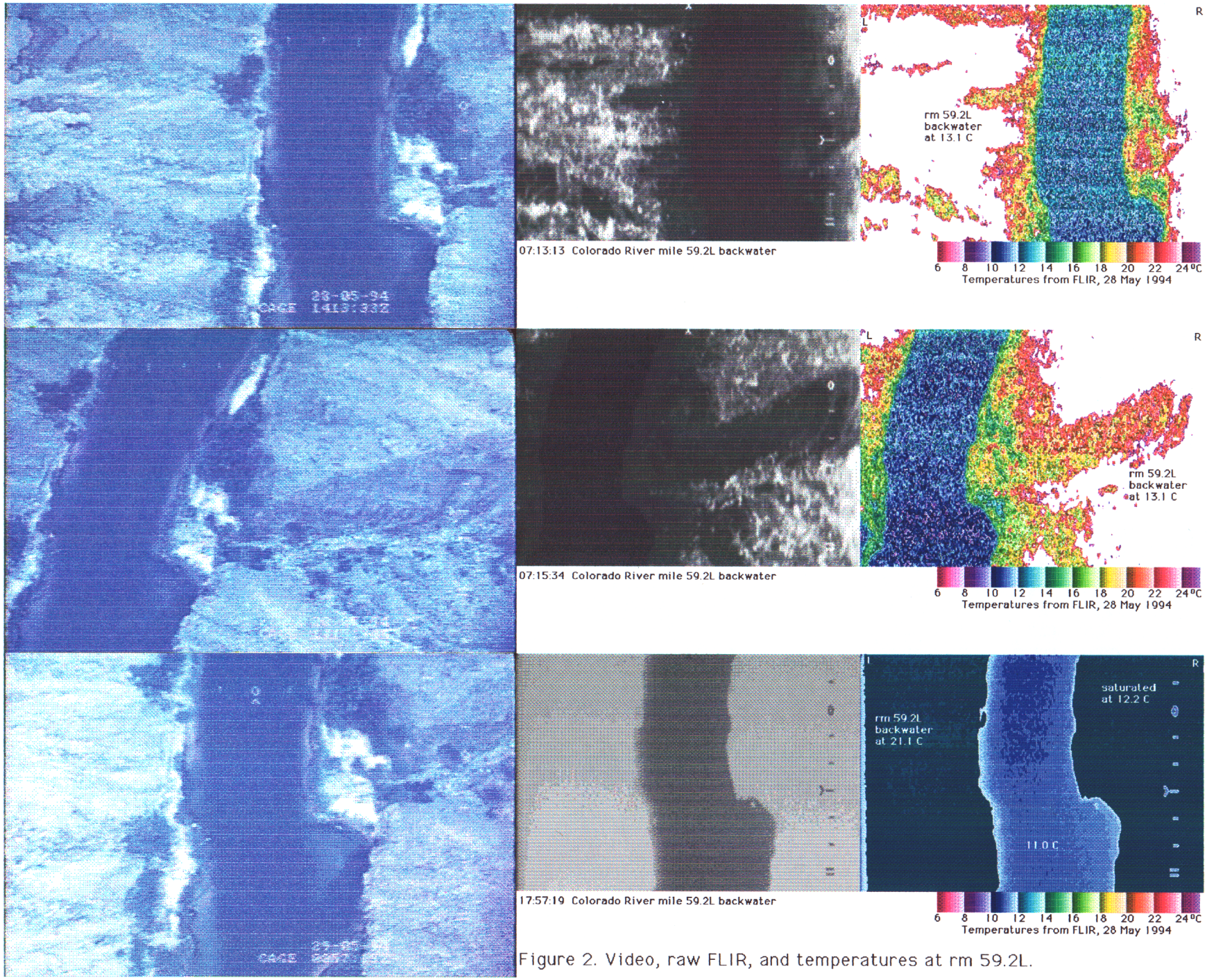

Figure 2. Video, raw FLIR, and temperatures at rm 59.2L.

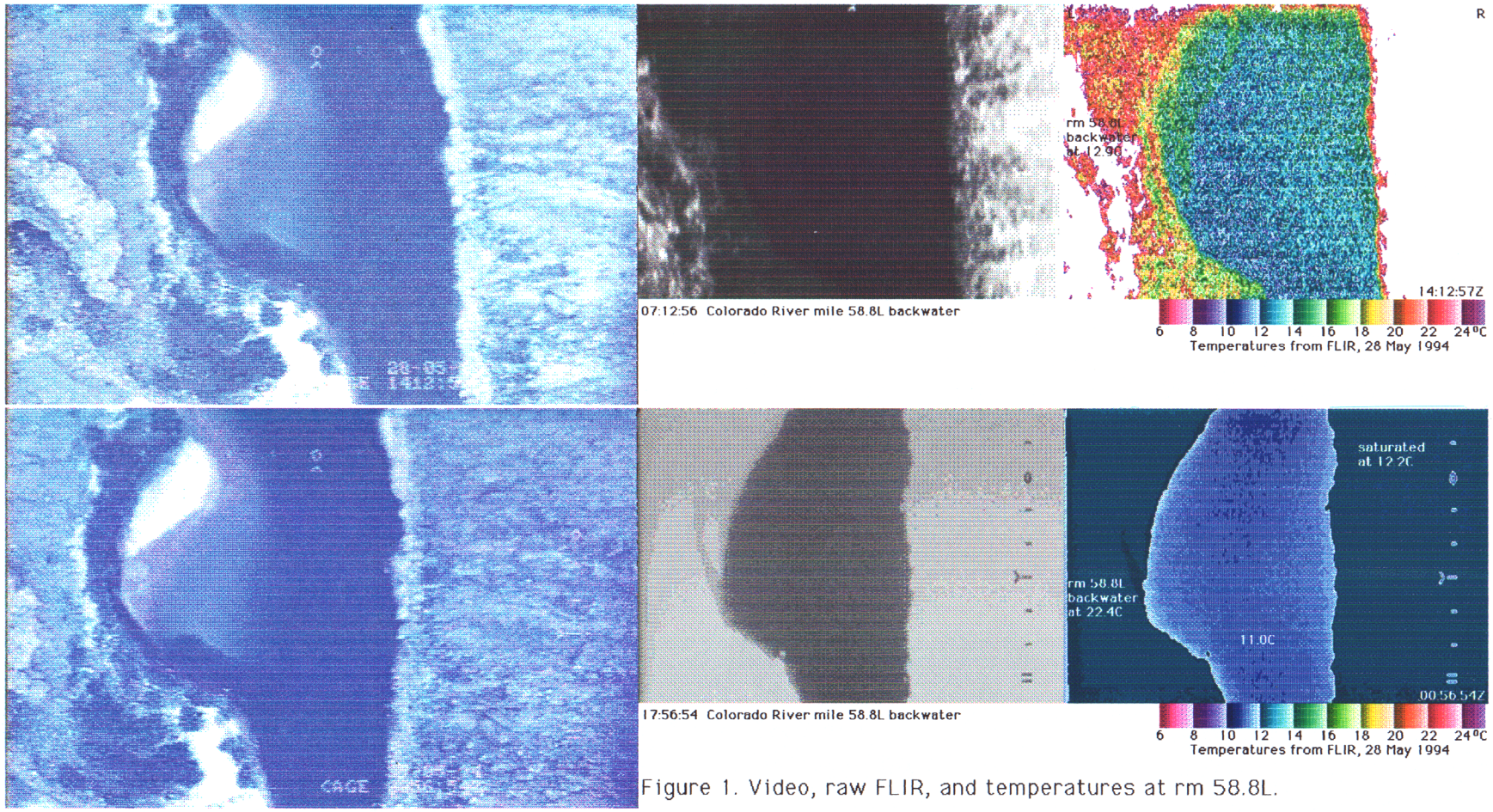

Figure 1. Video, raw FLIR, and temperatures at rm 58.8L.