# P12.2 AN ANALYSIS OF THE 7 JULY 2004 ROCKWELL PASS, CA TORNADO: HIGHEST ELEVATION TORNADO DOCUMENTED IN THE US


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## 1. INTRODUCTION

At 2337 UTC (4:37 PM PDT) July 7, 2004, a backpacker in the Rockwell Pass area of Sequoia National Park (west of Mt. Williamson in the southern Sierra Nevada) photographed a tornado (Fig. 1). The tornado had developed northwest of Rockwell Pass over the upper sections of the steeply-walled Kern River Canyon (Fig. 2). Since the elevation of Rockwell Pass is approximately 3500 m (~11600 ft), we believe this to be the highest elevation tornado photographed and documented in the United States .


Figure 1 – Developing tornado near Rockwell Pass in Sequoia National Park, 7 July 2004. Note swirl on lowered base. The sense of the rotation is counterclockwise. View towards the northwest. (Photo by Scott Newton)

Observers estimated that hail exceeding severe limits accompanied the storm and covered the ground in places. The former observation is corroborated by photographs of the hail (Fig. 3).


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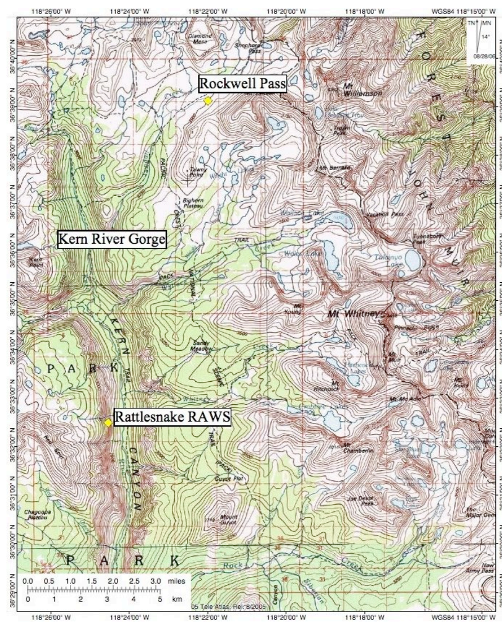


Figure 2 –USGS topographic map showing location of Rockwell Pass, the Rattlesnake RAWS site and the Kern River Canyon, as explained in the text.

Figure 3 – Severe-sized hail collected by photographer during thunderstorm associated with the Rockwell Pass tornado. (Photo by Scott Newton)


Figure 4 –Rockwell Pass tornado at approximately 2342 UTC (4:42 PM PDT). Note debris at funnel base and large hail falling. (Photo by Scott Newton)

Figure 5 – Panoramic photograph of thunderstorm that spawned Rockwell Pass tornado taken on 07 July between Lone Pine and Keeler, CA, at 2317 UTC (4:17 PM PDT), looking to the northwest. Note the backsheared anvil and overshooting top. (Photo by Bill Hensley)

The tornado circulation quickly propagated to ground level. Later photographs show considerable debris entrained into the condensation funnel (Fig. 4). In several of the photographs the fall of large hail is evident.

Photographs of the developing thunderstorm from about 30 km to the southeast (Fig. 5) show a number of interesting features. These include a well developed and crisp anvil with backshear, and the suggestion of an overshooting top, which would have been centered over the headwaters of the Kern River Canyon (Fig. 2).

Although tornadoes are not rare in California (as discussed in Monteverdi et al. (2003) and many other studies), documentation on tornadoes in the mountainous areas of California (or in any state) is sparse. By coincidence, a tornado that occurred in the same general geographic area was observed and documented in the late 1970s (Bluestein 1979). The most famous and well-documented high mountain supercell tornado was the F4-rated Yellowstone/Teton Wilderness tornado of 1987 (Fujita 1989). Interestingly, this tornado and parent thunderstorm formed in an area with topography as rugged as that in the southern Sierra Nevada, although elevations in the Rockwell Pass area are much higher.

The purpose of this paper is to present a brief examination of the synoptic and thermodynamic controls of this event. Since the photographic documentation presented above suggested to the authors that the parent storm may have been a supercell, we took special care in establishing the shear setting, to the degree it was possible, and examining the available radar information.

## 2. DATA SOURCES AND METHODOLOGY

The location of this event (Figs. 2 and 6) presents a challenge in documenting the Rockwell Pass storm meteorologically. First, although there are several surface observation sites nearby, they are located in the Owens Valley to the east, at a much lower elevation, and in a desert environment. Second, although the Weather Surveillance Radar 88 Doppler (WSR-88D) at KHNX was located fairly close to the event, the eastern portion of Sequoia National Park is topographically blocked from the radar's field of view. Third, the tornado location was in the midst of the National Weather Service (NWS) radiosonde sites at Oakland (KOAK), Reno (KREV), Desert Rock (KDRA) and Vandenberg Air Force Base (KVBG). All of these were distant enough from the tornadic storm to strain the direct use of their data to establish its proximity thermodynamic and shear environment.

The authors made a number of judgments in order to establish the storm's setting. First, the Department of Defense's (DOD) Doppler radar at Edwards Air Force Base (KEYX; Fig. 6) actually did observe the Rockwell Pass thunderstorm, though from a great distance. Since the Level II data for KEYX is not archived, the authors were constrained to use the Level III data. Unfortunately, since the KEYX radar was in Clear Air Mode on the day of the Rockwell Pass tornado; the highest reflectivity detectable in this mode is 28 dBZ.

Second, in establishing the synoptic setting, we noted that an unseasonably-strong trough in the middle and upper troposphere was progressing across the coastal waters off south-central and southern California the day of the event, spreading southwesterly flow aloft over the storm genesis area. Thus, we felt that the sounding information for KVBG at 0000 UTC 8 July 2004, located upstream and southwest of the Rockwell Pass area, would be the most representative in understanding the thermodynamic and wind setting for the event.

Third, while we could use the temperature, dew point and wind information from KVBG for the portion of the environment from 700 mb or so and above (the rough elevation of the Rockwell Pass area), we needed to establish the conditions in the convective boundary layer (CBL) or inflow layer for the storm. Fortunately, there was data available for the Remote Automated Weather Station (RAWS) Rattlesnake, located in the Kern River Canyon about 15 km or so south of Rockwell Pass (Fig. 2).

We used the temperature, dew point and wind information for 2300 UTC 7 July 2004 from Rattlesnake (at 3100 m elevation) as the surface data for the proximity sounding. We modified the sounding graphically so that a superadiabatic layer was found only in the lowest gate (skin layer) of data. Our procedure was to warm every level above the surface to about 420 mb; at that level the dry adiabat touched the environmental lapse rate of the modified KVBG sounding. This yielded a realistically-shallow superadiabatic layer near the surface and a well mixed, dry adiabatic CBL above Rockwell Pass.

We varied the wind direction and wind speed geometrically from the surface to 1000 m above ground level (AGL), the height of the walls of the Kern River Canyon. At that elevation the wind direction and wind speed then were those that we obtained from the KVBG sounding for that elevation.

## 3. SYNOPTIC SETTING

During the morning and afternoon of 7 July 2004, an unseasonably strong trough in the middle and upper troposphere, embedded in a subtropical branch of the westerlies, was located over the offshore waters west of south-central and southern California (Fig. 7a). This trough remained anchored for several days, while several shorter wavelength disturbances passed around it. One such disturbance moved across the coastline during the day on 7 July 2004 and its axis at 0000 UTC 8 July extended from near Santa Maria southeastward, more or less parallel to the coastline.

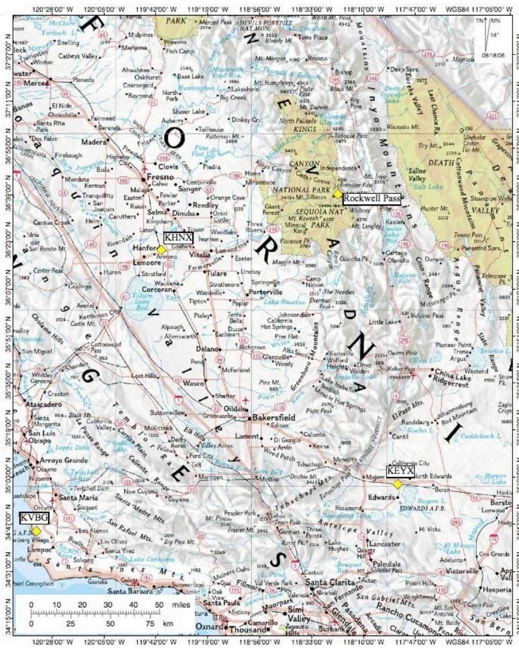


Figure 6 –Map of south-central California, showing locations of Rockwell Pass, KHNX, KVBG and KEYX, as discussed in the text.

The Rockwell Pass storm (indicated by the T on Figs. 7a and b) developed very close to the neutral point in the deformation zone northeast of the 300 mb trough axis. The authors obtained NCEP reanalyses of the 0000 UTC 8 July 2004 gridded data. Northeast of the incoming trough, weak synoptic-scale lift, undoubtedly augmented orographically, was evident over the storm genesis area at all levels from 850 mb (Fig. 7a) through 450 mb, far above the tops of the mountains.

That this source of layer lifting was dynamically-induced is suggested by the fields shown in Fig. 7b. The arrow indicates the sense of the thermal wind vector in a region of strong cyclonic vorticity advection by the 1000-500 mb thermal wind. This is proportional to the quasigeostrophic forcing for synoptic-scale lift at 700 mb.

This forcing was not at all evident from a glance at the height/vorticity or the temperature advection fields in the middle and upper troposphere (not given). We believe it to be the consequence of a complicated interaction between the "traditional" dynamics normally ascribed to features such as short wave troughs with the forcing associated with strong thermally-induced circulations related to the surface North American Thermal Low (NATL). The heated air associated with the NATL is evidenced by the area of high thickness values over the Four Corners area (noted as the thickness High on Fig. 7b).

These dynamic controls establish this case as much different than that documented by Bluestein (1979). In that case, a misocyclone tornado (also known popularly as a "landspout") occurred in association with a monsoonal thunderstorm developing in an environment absent the dynamics evident in the Rockwell tornado case. In essence, the synoptic environment for the Rockwell tornado case resembled that of the typical supercell tornadic thunderstorm cases observed in California during the cold season (Monteverdi et al. 2003) and elsewhere in the Great Plains, typically.

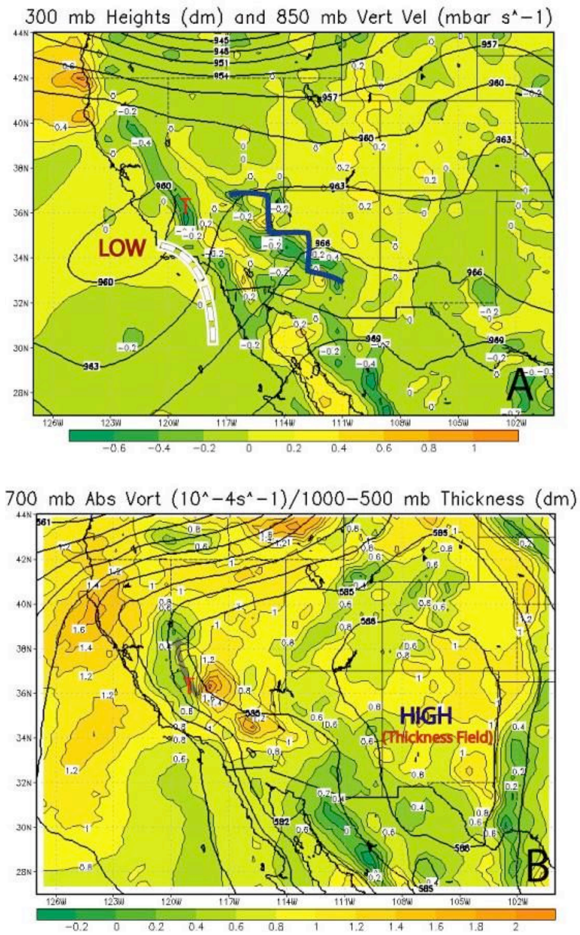


Figure 7 – NCEP reanalyses at 0000 UTC 8 July 2004 showing (a) 300 mb heights (dm) and 850 mb vertical velocity (μbar $s^{-1}$); and, (b) 1000-500 mb thickness (dm) and 700 mb absolute vorticity ($10^{-4}$ $s^{-1}$). Location of Rockwell Pass storm shown as "T". Arrow on (b) indicates the thermal wind, and can be used to infer the region of cyclonic vorticity advection by the thermal wind and quasigeostrophic forcing for upward motion at 700 mb.

We believe that the advancing trough also had an important role in moistening the middle troposphere with relatively high dew points. Plots of relative humidity for 0000 UTC 8 July 2004 from the lower to the middle troposphere show a large area of high relative humidity extending from trough axis downstream across the ridge axis (not shown).

The advance of the high dew points and relative humidity across south central and southern California can be followed in the satellite imagery (Fig. 8). The development of the Rockwell Pass storm can be seen in the two panels of Fig. 8. Note that the northern edge of the regionally developing cloudiness appears to be the axis of dilatation in the deformation zone north of the 300 mb trough seen in Fig. 7a.

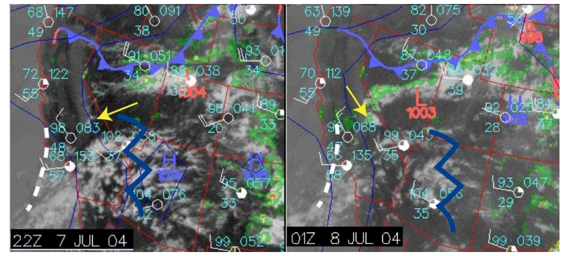


Figure 8 – Fronts and selected surface observations and infrared satellite imagery for selected hours on the day of the Rockwell Pass tornado. White dashed/blue jagged line show the positions of the 300 mb short wave trough and downstream ridge (as explained in the text) at the same times. Yellow arrow shows the position of the Rockwell Pass thunderstorm. (Charts courtesy of Unisys)

## 4. THERMODYNAMIC AND SHEAR SETTING OF ROCKWELL PASS STORM

The Rockwell Pass storm developed in an environment supportive of supercell convection. Various parameters obtained from proximity sounding and hodograph (Fig. 9; Section 2) are given in Table 1.

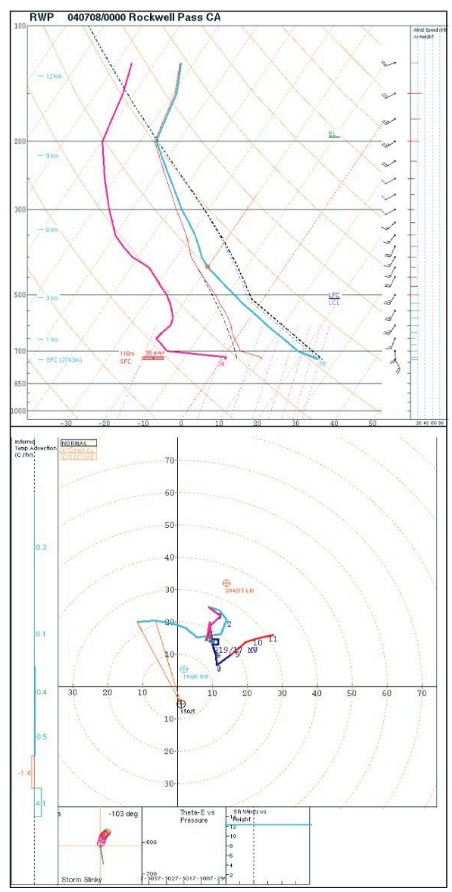


Figure 9. Proximity sounding and hodograph (generated by NSHARP) at 0000 UTC 8 July 2004, as explained in the text.

It is apparent that the strong boundary layer upvalley flow that developed in the Kern River Canyon (as estimated from the Rattlesnake RAWS and also seen in the observations for KBIH and other RAWS sites [not given]) by late afternoon had a significant role in producing a thermodynamic and shear profile favorable for long-lived deep convection. The values of 0-6 km shear and the Bulk Richardson Number (BRN) obtained from the proximity sounding and hodograph (Table 1) are in the range consistent with supercell convection (Weisman and Klemp 1986).

| | |
|---|---|
| sbCAPE | 1368 J/kg |
| 0-6 km Shear | $5.5 \times 10^{-3}\ s^{-1}$ |
| 0-3 km Storm Relative Helicity | $146\ m^2\ s^{-2}$ |
| Actual Storm Motion | 350/5 kts |
| 0-1 km Shear | $11.0 \times 10^{-3}\ s^{-1}$ |
| BRN | 20 |

Table 1: Parameters calculated on the basis of the 0000 UTC proximity sounding and hodograph for the Rockwell Pass area given in Fig. 9 and explained in Section 2.

The low level shear environment seemed also to be favorable for low level mesocyclone and, possibly, tornado development. The 0-3 km storm relative helicty (SREH) is consistent with the development of at least a weak mesocyclone. The 0-1 km shear value is in the top third of such values observed for California tornadic thunderstorms, documented in Monteverdi et al. (2003).

## 5. RADAR EVOLUTION OF ROCKWELL PASS STORM

Since the WSR-88D radar site at KEYX (Fig. 6) was quite distant from the storm (about 190 km), the storm radar echo is only observable on the lowest three elevation angles (0.5°, 1.5°, 2.4°). This presents some challenges in the radar diagnosis of the event.

The approximate height of the centerline of the radar beam at these three elevation angles is provided in Table 2. Also, at this range, the 1° radar beam width is quite wide (about 3200 m), and the radar data is more or less averaged in a volume that is centered on the elevations shown in Table 2. These height values also assume standard atmospheric propagation.

The first indication of a radar echo observed from KEYX is at 2152 UTC on 7 July 2004 at the 1.5° elevation scan, about 1 h 45 m prior to the tornado. The echo continued to expand and develop. For the next several hours it remained mostly anchored to the high terrain, moving slowly southward at about 2-3 m $s^{-1}$, until about 0030 UTC 8 July 2004, when it started to weaken and move east before dying. At no time, was there any echo observed at the 3.3° elevation or higher, indicating that the storm summit never exceeded a height between 11142 – 14464 m (about 36,000 – 47,000 ft).

An analysis of the Doppler radial velocity data was performed by the authors. A storm-top divergent signature of 11 m $s^{-1}$ (22 kts) is already apparent at 2212 UTC on the 2.5° tilt. Divergence increases to 20 m $s^{-1}$ (40 kts) by 2241 UTC, about one hour prior to the tornado. Also, weak cyclonic shear from 8-11 m $s^{-1}$ (15-22 kts) exists off and on from 2221 - 2310 UTC at the 0.5° tilt.

| | Height of Radar Beam | | |
|---|---|---|---|
| Elevation Angle | Above Sea Level | Above Radar Elevation | Above Rockwell Pass |
| 0.5° | 4859 m | 3719 m | 1053 m |
| 1.5° | 7881 m | 7010 m | 4345 m |
| 2.4° | 11142 m | 10272 m | 7606 m |
| 3.3° | 14464 m | 13594 m | 10929 m |

Table 2: The height of the centerline of the radar beam at 190 km range at various elevation angles. The 1° beam width is about 3200 m at these ranges.

The storm was too distant for KEYX to observe any of the reflectivity characteristics typically associated with supercells, such as a low-altitude hook or pendant echo, or a bounded-weak echo region (BWER). However, there is evidence of an echo overhang and an indication of an intense updraft, particularly 20 minutes on either side of the reported time of the tornado (2337 UTC 7 July 2004).

Figure 10 depicts the radar reflectivity at the lowest four elevation angles at the volume scan closest to tornado time. Note that there is considerably more echo south of the tornado location (red dot) at the 1.5° and 2.4° elevation scans than at the 0.5° elevation scan, indicative of a possible echo overhang. However, it should be noted that the data at 0.5° could be partially attenuated by terrain blocking the lower portions of the radar beam. Other taller surrounding terrain (including, perhaps, even Mt. Whitney) is certainly blocking a portion of the radar beam at 0.5°.

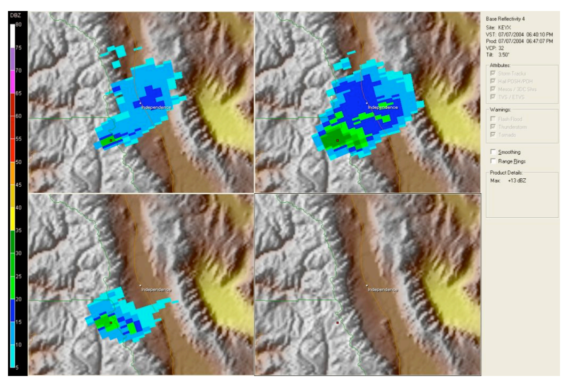

Figure 10. Radar reflectivity at 0.5°, 1.5°, 2.4°, and 3.3° elevation angles from KEYX at 2340 UTC 7 July 2004. Location of the tornado at Rockwell Pass is shown as a red dot.

Figure 11 depicts the Doppler radial velocity at 0.5°, 1.5°, and 2.4° (along with 0.5° reflectivity) at the volume scan closest to tornado time (2340 UTC). Observable at this time is 15 m $s^{-1}$ (30 kts) convergent cyclonic shear at 0.5° deg, 11 m $s^{-1}$ (22 kts) of symmetric cyclonic shear at 1.5°. These values correspond to a weak-to-moderate strength mesocyclone using the definitions supplied by Stumpf et al. (1998; "Strength Rank" of 3 or 4). There is also 16 m $s^{-1}$ (33 kts) of divergence near the storm summit, another indication of a robust storm updraft.

The authors stress the limitations of the KEYX radar observations of the Rockwell Pass storm. These included far range, partial terrain blockage, and availability of only the clear-air mode data. Even so, the radar evidence alone suggests that this storm was a supercell.

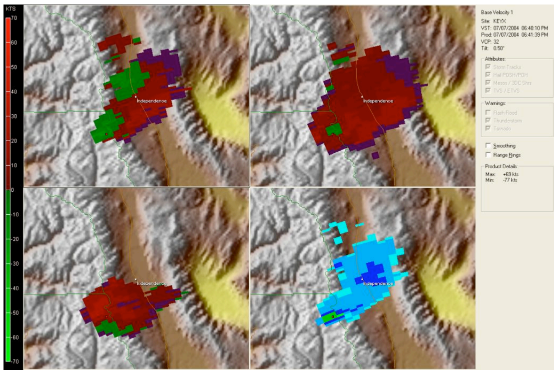

Figure 11. Doppler radar radial velocity at 0.5°, 1.5°, and 2.4° elevation angles, and reflectivity at 0.5° elevation angle from KEYX at 2340 UTC 7 July 2004. Location of the tornado at Rockwell Pass is shown as a red dot.

## 6. CONCLUSIONS

The authors were faced with the task of documenting a tornadic thunderstorm that had developed in a remote location, far removed from upper air and WSR-88D observation sites. In establishing the thermodynamic and shear setting for the storm, the authors made a number of assumptions to estimate the observations for the lowest 1000 m of the thunderstorm's inflow layer. These were used to modify the KVBG mandatory and significant level temperature, dew point and wind information to produce an estimated proximity sounding and hodograph, as explained in Section 2.

The available radar information was also sparse. KHNX, the nearest WSR-88D site, was topographically blocked. The next closest radar site, KEYX, was in clear air mode and nearly 200 km from the storm.

Despite these issues the authors believe that the combination of the tornado and storm photographs with the interpretation of the thermodynamic, shear and radar evidence, suggests that the Rockwell Pass tornado was not only the highest elevation tornado ever documented in the United States, but was also probably associated with a supercell. None of the evidence allows us definitively to conclude that the tornado itself was supercellular. It is not unusual for tornadoes to develop in association with supercells but unrelated to the mesocyclone. However, the evidence, while circumstantial, is strongly suggestive that the Rockwell Pass tornado was mesocyclone-induced.

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## 8. ACKNOWLEDGEMENTS


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