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Detection of a Unique Earthquake Swarm in Eastern Arizona

Kevin C. Eagar and Matthew J. Fouch
School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287

ARIZONA, UNLIKE CALIFORNIA TO THE WEST, is a region that rarely experiences significant or even detectable earthquake activity, yet there is the potential for destructive earthquakes across much of the state as evidenced by historical seismicity (Figure 1). The capabilities of the U.S. Geological Survey to detect earthquakes in the region are limited to magnitudes of approximately $m_b \geq 4.5$, and local monitoring of seismicity in the state has limited coverage. There is thus a significant missing component of the regional earthquake record that limits our ability to understand long-term deformation and potential seismic risk and hazard for a significantly large area of the southwestern United States.

Over a period of two days from December 21 to 22, 2003, a swarm of at least twenty small magnitude earthquakes occurred in eastern Arizona, just west of Hannegan Meadow and ~80 km (50 miles) southwest of the Springerville/Eagar area. The location of the swarm was proximal to the boundary between the Colorado Plateau, a topographically elevated region that is relatively undeformed, and the Arizona Transition Zone, an area of high relief between the Colorado Plateau and the extended lowland terrain of the southern Basin and Range. This episode confirms that eastern Arizona continues to be an active region of tectonic deformation, where regional strain is at least in part being accommodated by brittle failure.

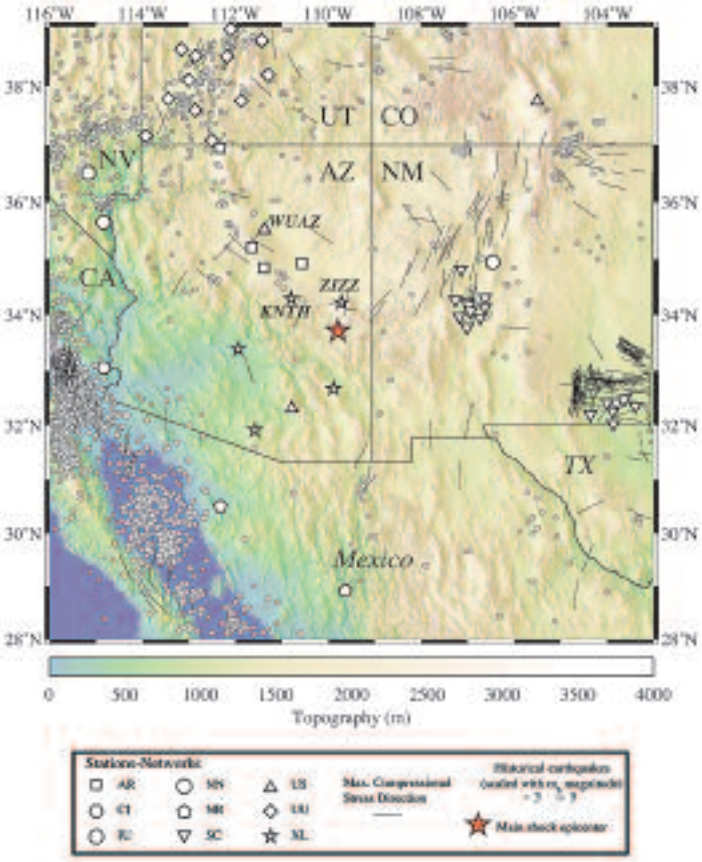

Figure 1. Map of seismic stations used in this study. COARSE array (XL) stations are denoted by white stars, the Northern Arizona network stations (AR) are shown as white squares, the Caltech network station (CI) is shown as a white hexagon, the Global Seismograph Network station (IU) is shown as a white circles, the Western Great Basin/Eastern Sierra Nevada network stations (NN) are shown as white octagons, the NARS array stations (NR) are shown as white pentagons, the New Mexico Tech seismic network stations (SC) are shown as white inverted triangles, the US National seismic network stations (US) are shown as white triangles, and the University of Utah regional network stations (UU) are shown as white diamonds. The red triangle denotes the location of the largest event in the swarm (main shock). Black bars show orientations of maximum compressional stress from the World Stress Map (Reinecker, et al., 2005). Gray circles show locations of historical earthquakes from the ANSS earthquake catalog, with the size scaling to m_b magnitude.

TECTONIC BACKGROUND

The tectonic evolution of the Colorado Plateau, the southern Basin and Range, the Arizona Transition Zone, and the Rio Grande Rift tectonic provinces in eastern Arizona and western New Mexico (Figure 1) is still debated. Key questions include: a) What is the tectonic relationship between the Colorado Plateau to the Basin and Range?; b) How is strain in the lithosphere accommodated in this region?; and c) What are the short-term and long-term rates of deformation in this region? For example, there is evidence that the Rio Grande Rift is tectonically active by the presence of the Socorro magma body at mid-crustal depths and the occurrence of earthquake swarms associated with it (i.e. Balch, et al., 1997; Schlue, et al., 1996). The Socorro magma body has experienced active magma intrusions as current as the mid-1990s (Fialko and Simons, 2001). Late Cenozoic volcanism in the Springerville volcanic field suggests that tectonic activity on the southern periphery of the Colorado Plateau has

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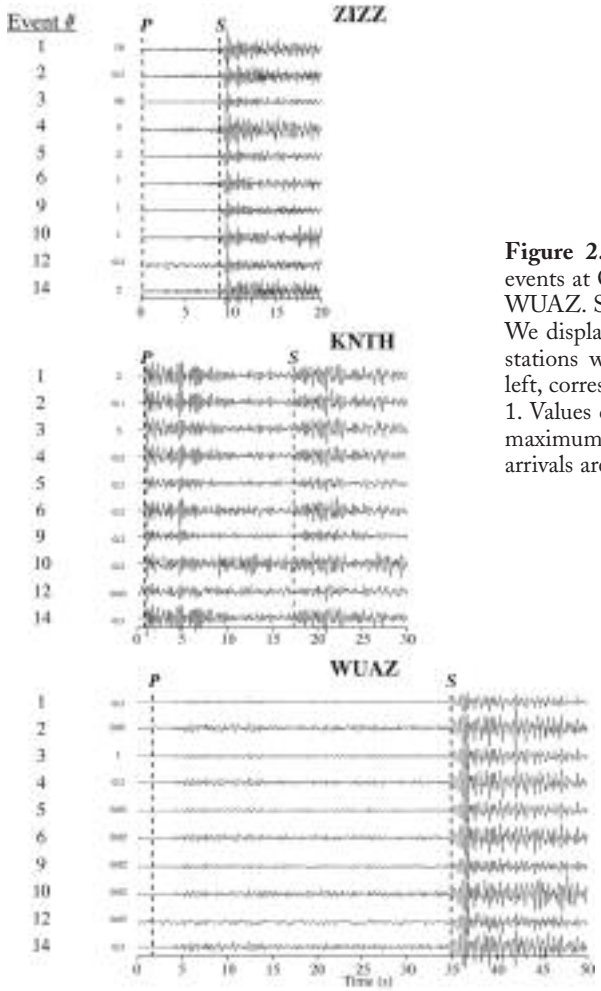

Figure 2. Vertical seismograms from swarm events at COARSE stations ZIZZ, KNTH, and WUAZ. Station locations are labeled in figure 1. We display only the events recorded by all three stations with the event number labeled on the left, corresponding to the event numbers in table 1. Values directly left of each record indicate the maximum amplitude x 10^{14}. P- and S-wave arrivals are marked as the dashed lines.

also been recent (Condit and Connor, 1996). Evidence for regions of partial melt in the crust related to Quaternary volcanism has been suggested from teleseismic converted phases that characterize the bulk composition of the crust (Frassetto, et al., 2006).

Although there is a relative paucity of earthquakes in this region outside of the Rio Grande Rift, occasional earthquake activity and paleoseismic evidence suggests that Arizona and surrounding regions are not free from tectonic forces that could potentially lead to destructive earthquakes in the future. Notable earthquakes that have occurred in the region include the 1887 Sonoran earthquake, a M_S 7.4 in northeastern Sonora, Mexico (Natali and Sbar, 1982); the 1976 Chino Valley earthquake, a m_b 4.9 located 20 km north of Prescott (Eberhart-Phillips, et al., 1981); the 1992 m_b 4.5 Grand Canyon South Rim and 1993 m_b 4.9 Cataract Creek sequences; and the 2005 Winslow earthquake, a m_l 4.6 located near Winslow, Arizona (http://www4.nau.edu/geology/aeic/EQhistory.html). Fault scarps in the Santa Rita Mountains have also shown significant slip resulting from events estimated for a seismic moment of 6.4 to 7.3 in the mid-Pleistocene (Pearthree and Calvo, 1987). This evidence suggests small strain accumulation in this region, resulting in long earthquake recurrence intervals. However, without long-term earthquake monitoring from broadband seismic instruments, this recurrence interval remains speculative.

Data and Methods

In late December, 2003, seismic stations in the COARSE array, deployed by Arizona State University and the University of Arizona (http://asuarray.asu.edu/COARSE), detected several unexpected local earthquakes within a two day period. We gathered waveform data from COARSE array stations as well as other seismic networks in the area to locate and characterize the events (Figure 1). We employed a short-term amplitude versus long-term amplitude ratio (STA/LTA) detection algorithm to search through the continuous data stream and flag potential earthquakes, after which we individually inspected the flagged events. Locations and magnitudes for the earthquakes were obtained using the

TABLE 1: EARTHQUAKE CLUSTER EVENT CATALOG

Event #	Date (MM/DD/YYYY)	Origin Time (GMT) (HH:MM:SS.S)	Latitude (°N)	Longitude (°E)	Depth (km)	m_l	# stations
1	12/21/2003	16:01:42.1	33.70	-109.78	0.0	3.9	8
2	12/21/2003	16:06:51.0	33.68	-109.50	0.0	3.3	6
3	12/21/2003	16:08:57.2	33.62	-109.78	0.0	4.2	8
4	12/21/2003	16:12:58.3	33.72	-109.80	0.0	3.9	8
5	12/21/2003	16:19:36.6	33.68	-109.55	0.0	3.4	7
6	12/21/2003	16:24:01.8	33.68	-109.56	0.0	3.2	7
7	12/21/2003	17:15:59.5	33.63	-109.62	0.0	3.3	4
8	12/21/2003	17:26:25.9	33.52	-108.72	21.9	3.6	2
9	12/21/2003	17:30:50.0	33.67	-109.52	0.0	3.3	5
10	12/21/2003	18:07:11.0	33.69	-109.5	7	0.0	3.4
11	12/21/2003	18:07:18.2	33.66	-109.46	0.0	3.4	5
12	12/21/2003	19:07:03.0	33.68	-109.52	0.0	3.2	4
13	12/21/2003	19:28:49.7	33.51	-108.67	44.8	3.5	2
14	12/21/2003	19:32:57.7	33.70	-109.78	0.0	3.5	8
15	12/21/2003	21:28:21.9	33.80	-109.07	0.0	3.6	2
16	12/22/2003	02:48:44.1	33.75	-109.26	25.4	-	2
17	12/22/2003	05:08:01.1	33.77	-109.22	28.8	3.3	3
18	12/22/2003	06:43:59.3	33.77	-109.22	28.8	3.2	3
19	12/22/2003	10:08:11.5	33.85	-109.13	34.1	3.3	4
20	12/22/2003	11:08:27.8	33.78	-109.29	29.0	3.3	3

dbgenloc software (Pavlis, et al., 2004) and a 1D velocity model for the Arizona Transition Zone adapted from Warren, 1969. We hand-picked P and S arrivals on these seismograms and determined the location of one m_l 4.2 earthquake that occurred on December 21, 2003 in eastern Arizona, southwest of Springerville (Figure 1). Upon further inspection of the seismic records, however, we found several other local earthquakes within minutes of this event and also located these events very close to the main event detected by our STA/LTA detection algorithm. The local magnitudes from the entire swarm range from 4.2 to 3.2, and epicentral depths are generally located at 0 km (i.e., very near surface) (Table 1). We note that depth is by far the least constrained parameter in the location of these earthquakes due to both the uncertainties related to the velocity model as well as the sparse regional station coverage. However, because Pn waves, refracted waves that travel along the crust-mantle interface (the "Moho") at uppermost mantle velocities, were recorded at regional stations, the sources must originate within the crust. The events in this earthquake swarm do not appear to be individually isolated, as the waveform shape, frequency content, and timing between seismic phases were nearly identical among the group (Figure 2). This striking similarity in waveform character is rare and suggests that the source location and mechanism for all of the events are also similar.

To gather a complete catalog of swarm events, we searched for other events recorded by the COARSE array that showed similar waveforms as the swarm events. Since all but one of the events were below our STA/LTA detection levels, we implemented a cross-correlation algorithm to examine all waveforms for events that may have been missed by other means including visual inspection. In this method, we selected the largest earthquake (termed the "main shock") in the swarm as a master event. We then used the master event in a matched filter detection algorithm that cross-correlated the master event with the continuous seismic data for each station. The advantages of matched filter detection are two-fold. First, we were able to discover several otherwise undetectable events possessing a low signal-to-noise ratio (SNR) to get a more accurate count of the total number of swarm events, enabling us to put tighter constraints on the full character of the swarm. Second, we were able to obtain very accurate relative arrival times for each event by using the cross-correlation function peaks from the continuous data. Although this provides no improvement on absolute locations, the relative locations of the earthquakes in the swarm are dramatically improved with this technique.

For the master event, we chose a time window beginning at 2-5 seconds before the observed P-wave arrival and ending when the energy dropped to background levels. This time window varied for each station depending on the length of the coda. We then filtered the master event and the continuous data with a 1-5 Hz bandpass filter. We used the matched filter algorithm for each station to cross-correlate the master event with continuous waveform data within a 20 day period surrounding the master event using a 1 sec time step between each correlation to compute a time series of correlation coefficients. We defined a detection as an instance where the correlation coefficient exceeded a threshold value of 0.5. Using this criterion resulted in no false detections originating from the automatic detection algorithm.

We used this procedure to detect a total of 20 earthquakes on at least two stations, and 16 that were detected on at least three stations (Table 1). Based on these detections, we determined that the first earthquake in this swarm occurred on December 21, 2003 at 16:01:42 GMT and that the last occurrence occurred on December 22, 2003 at 11:08:28 GMT for a total swarm duration of ~19 hours. No other earthquakes in this region occurred recently prior to or after these events.

In an effort to provide an estimate of the focal mechanism for the swarm, we determined first-motion P-wave polarities at stations where the SNR was large enough to pick the first break of the arrival. We assumed that the polarities for the main shock (event 3 in table 1) are representative of all the swarm events due to the extreme similarities among event waveforms for each station. For stations closer than about 120 km to the epicenter, the direct P-wave traveling through the crust is observed as the first arrival. However, at further distances, the Pn wave arrives first. Due to source-event distances, only five stations were close enough to observe P as the first arrival.

Visual inspection of the observed polarities did not yield a discernable pattern that would suggest a double-couple earthquake source (Figure 3). We therefore attempted to determine the focal mechanism using a grid-search for the suite of best-fitting focal mechanisms using the approach of Hardebeck and Shearer, 2002 and the HASH software (Hardebeck and Shearer, 2002). Unfortunately, the uncertainties in focal mechanism geometry were too large to yield a reliable result. Reasons for the uncertainty in this analysis include the absence of a comprehensive crustal velocity model for this region, which would reflect the local complex structure of the crust over small spatial scales.

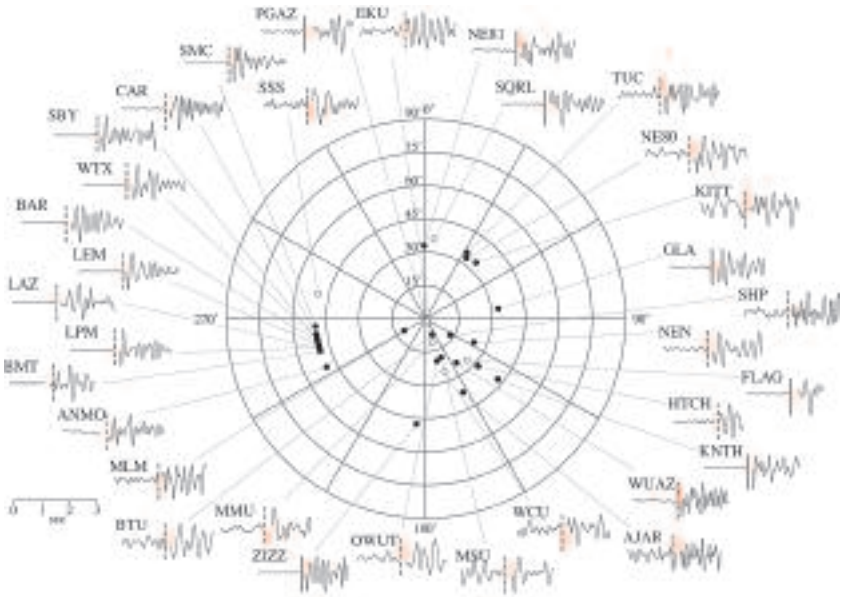

Figure 3. Upper-hemisphere first-motion data for the main shock swarm event. First-motions are plotted at back-azimuth vs. takeoff angle from the event. The filled circles denote compression (first-motion up) and open circles denote dilatation (first-motion down). Corresponding vertical seismograms bandpassed at 1-5 Hz are linked to each data point, where the red portion shows the interpreted first-motion. The solid bars show the time of the cross-correlated P-wave direct arrival, whereas dashed bars indicate stations where the first arrival was the Pn wave.

In an attempt to alleviate some of these issues, we therefore used three different P-wave velocity models based on the ray path from the source to each station and assigned a 1D model to that station based on these determinations. We used specific velocity models for the Basin and Range and the Arizona Transition Zone from Warren, 1969 and a Colorado Plateau velocity model from Leidig, et al., 2005 to determine path-specific take-off angles for the focal mechanism determination. However, even after applying this correction, the grid-search results remained unreliable and we therefore were unable to determine a focal mechanism for the swarm.

As disappointing as it is to not reliably constrain the focal mechanism with the waveform data available for the swarm, it is clear that these events do not appear to be associated with blasting from the nearby open-pit Morenci copper mine. Mining activity is well-recorded by stations in our array and waveforms from the swarm show a clear departure in waveform character from Morenci blasts. In addition, no other blasting-related activity was recorded within many days of the swarm (likely due to the time of year of the swarm). Finally, the events are not temporally correlated with normal blasting schedules, which during this period in time typically occurred in the daytime hours on weekdays.

Conclusions and Future Steps

This study provides a first-order look at indications of present-day tectonic stress near the Arizona Transition Zone / Colorado Plateau boundary from the detection and analysis of a localized swarm of earthquakes in central Arizona. The locations of these crustal earthquakes confirm that this region is still tectonically active. Although Quaternary faults in the Arizona Transition Zone are northwest trending (Menges and Pearthree, 1989), these events are difficult to associate with any known surface structure. Given the general lack of small-magnitude earthquake occurrence in the region, it is very likely that many subsurface faults exist that have not yet been discovered.

Evidence of event clustering in Arizona such as that determined by the current study is highly unusual and suggests that the process of strain release in this region may be relatively simple. We submit that part of the reason for this swarm is that the geometry of stress in the region is relatively simple, thereby reducing the potential for variable source aftershocks. However, the observation of the swarm is currently unique for the region and may not reflect longer-term seismicity/strain relief. Nonetheless, the swarm as a whole is likely reflective of strain release within the longer-term earthquake cycle that is generally undetectable by the national seismic network due to the extremely limited station coverage in the area.

Current and future seismic station deployments in Arizona, such as the Earthscope USArray Transportable Array (TA) (Abbott and Cook, 2006; http://earthscope.org), should provide the data necessary for a significantly improved characterization of the earthquake process and regional tectonic structure. We note that at the time of this writing, data from the USArray TA have already yielded locations for several hundred seismic events (not associated with mining activity) that

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have occurred in the state over the past ~2.5 years (Frank Vernon, pers. comm., December 2007), providing a dramatic example of the expected improvement in seismic event detection using a modern broadband seismic array. Determinations of earthquake locations and focal mechanisms using these data will therefore provide essential new information on shallow crustal structure and earthquake patterns to improve on seismic velocity models and a fundamentally improved assessment of seismic hazards across the region.

Acknowledgements

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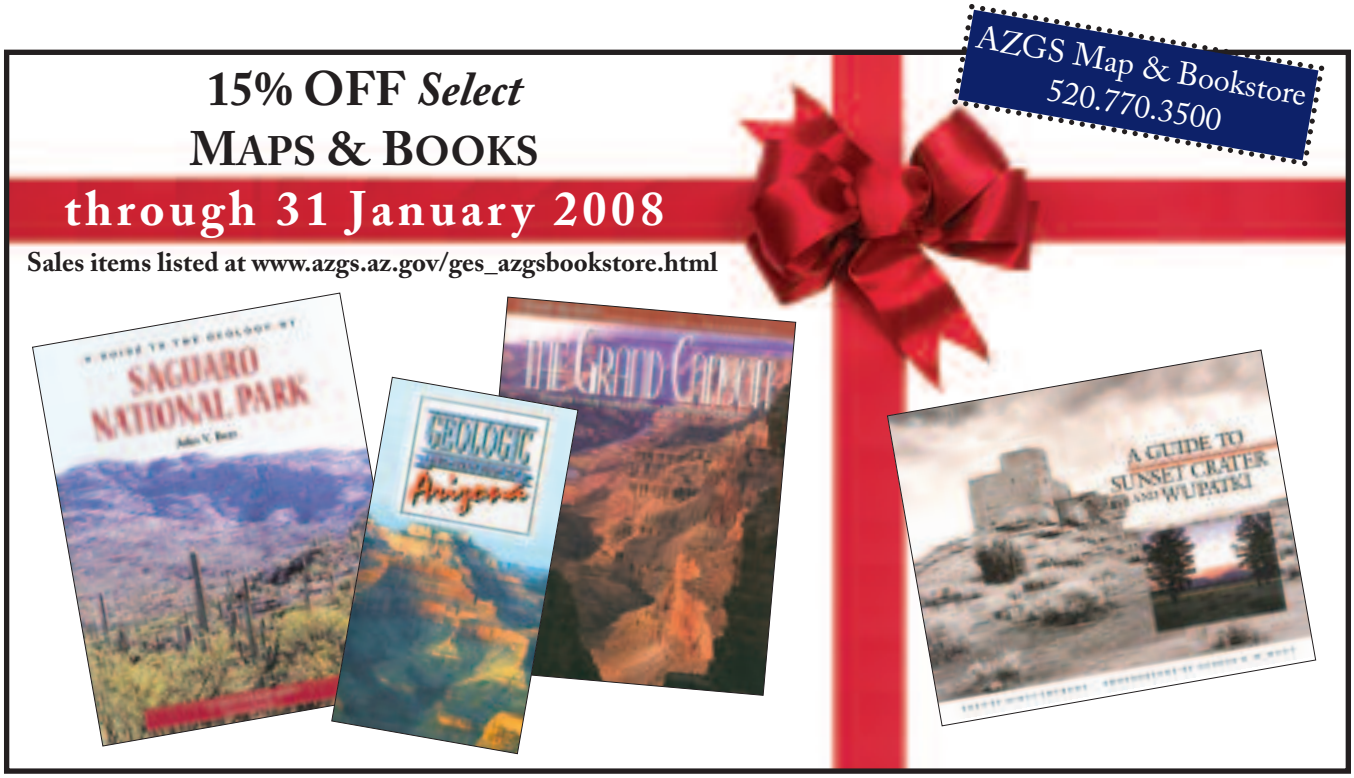

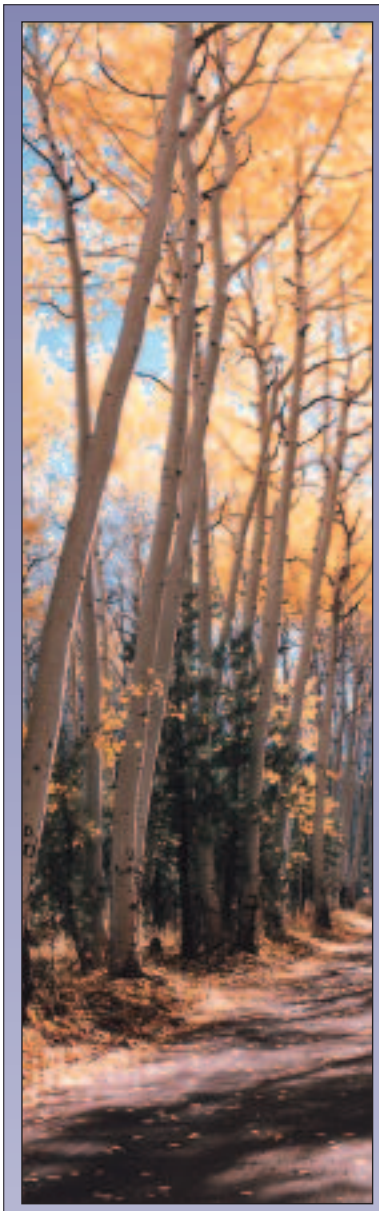

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