Eyewitness reports for the June 3, 2004 Pacific Northwest fireball

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Abstract– The fireball that illuminated much of the Pacific Northwest on June 3, 2004 provided an opportunity to see what could be learned about a bright fireball through eyewitness accounts by the public. Interviews were conducted over the telephone and in person with 60 observers located from as far north as Belfair, WA, to as far south as Bend, OR, and as far east as Spokane, WA. Data were entered on a fireball report form previously developed by personnel at the Cascadia Meteorite Laboratory. Based on eyewitness data, the fireball lasted ~4 seconds, and during this time the fireball appears to have broken into three main pieces which themselves fragmented. Four reports of sounds occurring during the fireball were received, supporting the idea that large fireballs can create "anomalous" or "electrophonic" sounds by some type of electromagnetic effect. Moreover, possible effects of an electromagnetic pulse were noted. We found that although most observers were not able to accurately estimate fireball azimuths or altitudes, an estimate of fireball trajectory could be obtained from the most specific and reliable reports. Based on these data, the fireball was first tracked near -122.48E ± 0.11E longitude and 46.69E ± 0.14E latitude at a height of 148 ± 41 km (1σ uncertainties). It was last tracked near -121.93E ± 0.20E longitude and 46.41E ± 0.17E latitude at a height of 33 ± 8 km. This implies a bearing towards ~122E and a descent angle of ~65E. Other eyewitness data imply that the fireball may have extinguished at a more northerly location, just north of the towns of Randle and Packwood, WA, close to the 1σ uncertainty and within the 2σ uncertainty for the estimated trajectory. We suggest that meteorites are most likely to have fallen somewhere in the vicinity of highway 12 between Randle and Packwood, or to the southeast towards the western boundary of the Goat Rocks Wilderness area. The eyewitness observations are inconsistent with seismic data suggesting still more northerly locations for the terminal burst of the fireball (Tatum, 2004; Matson, 2004). The reason for this discrepancy is unclear at this time.

INTRODUCTION

The bright fireball that lit up the Pacific Northwest at 2:40 am PDT on June 3, 2004 provided an opportunity for personnel at the Cascadia Meteorite Laboratory (CML) in Portland, OR, to evaluate whether scientifically useful information about a fireball could be obtained from surprised, untrained observers (the public). We received 60 eyewitness reports of the fireball as a result of television, radio, and newspaper coverage, together with a poster campaign we initiated in southwest Washington. Data obtained from eyewitnesses were entered on a standardized report form (Fig. 1, available on-line at http://meteorites.pdx.edu/CML_Fireball_form.htm), which we developed over the years. The report form includes queries about the location of the observer, the direction observers were facing, the name and contact information of the observer, the appearance, duration, sounds, and any smells associated with the fireball, and specific questions about azimuths and altitudes (Fig. 1). Data collection began as soon as ~20 minutes after the fireball. Key observations were clarified by phoning or meeting with observers up to 6 weeks after the event.

RESULTS AND DISCUSSION

Table 1 summarizes field data, with a separate number given to each observer. Although most of the observers making reports to us viewed the fireball from the greater Portland area, some were located far from Portland. Locations range from as far north as Belfair, WA, west of Seattle, to as far east as Spokane, WA, and as far south as Bend in central Oregon (Table 1). Fig.

2 shows the locations of observers in the Portland-Seattle-Cascade range corridor, which is where most of our observers were located. Most eyewitnesses were travelling in vehicles during the fireball event; others were awakened by it; and still others appear to have been in good positions to observe it. Below we present the results of our analysis of these eyewitness reports, focussing in turn on the brightness, appearance, and duration of the fireball; evidence for fragmentation; sound and other effects; and finally the trajectory.

Brightness, appearance, and duration of fireball. As noted above, eyewitnesses making reports to CML were spread over a large area. Media reports indicate that the fireball was seen even further north (Victoria and Vancouver, British Columbia) and even further east (Couer d'Alene, Idaho) than the observers making reports to us. This indicates that most of the Pacific Northwest was illuminated by the June 3 fireball. Clearly, this fireball was extremely bright, and comprises the first major fireball over the Pacific Northwest in the new millenium. Based on the brightness of the fireball, we suggest that the incoming meteoroid was large, in the "Volkswagon-size" range, with perhaps ~5 kiloton of energy.

Observers who saw the fireball reported that its central bright zone was up to several times the apparent diameter of the full moon (observers 13, 15, 20, 28, 29, 30, 33, 39, 40, 41, 42, 48, 57, 58). This implies an angular diameter of up to ~3 degrees, which is immense, and probably unrealistically large. White, yellow and orange were the most common colors reported (Table 1). Some observers noted a color sequence to the fireball, most commonly white or yellow changing to some other color (Table 1). This color sequence can be interpreted as a cooling trend caused by the slowing of the object as it encountered air resistance. One observer (59) noted the fireball left a smoke trail across the sky.

The duration of the fireball was estimated by different observers as being between 1-6 seconds. Averaging 40 observations yields a mean and standard deviation of 2.8 ± 1.3 seconds. As some observers only caught a glimpse of the fireball (e.g., near its terminus), the actual duration is probably $3 seconds. Using only estimates obtained from those observers whose data was used for trajectory analysis (see below) gives a mean and standard deviation of 3.6 ± 1.6 seconds. Based on eyewitness data, we suggest ~4 seconds as the best estimate for the fireball duration. This is reasonable for what one might expect for a fireball, and consistent with a ~3.6 second duration implied by a video recording (Matson, 2004).

Fragmentation. Eleven reports were received of the fireball breaking into several pieces or transforming into "sparks" (observers 20, 21, 26, 33, 36, 37, 44, 45, 50, 57, 58) (Table 1). These observers reported between 2-12 fragments. One observer (26) reported that the fireball had a flash, followed by a very bright flash, at which point the original fireball was actually 3 separate fireballs, one large and two small. Two main pulses of light were noted by others as well (observers 12, 17, 19, 25). Video recordings from cameras at the Harborview Medical Center (widely shown by the news media) record 3 pulses of light in the sequence bright- very bright- bright, suggesting three major fragmentation events. Reports we received of more numerous fragments, and of "sparks", suggest that the three main fireballs broke apart again. Such multiple fragmentation events lead us to suspect that the meteoroid responsible for the fireball was a stony, as opposed to metallic, object.

Sound effects. Two types of sound effects were reported, including what we will call "delayed" and "anomalous" sounds. Delayed sounds, occurring distinctly after the fireball, include "booms" and "rumbles", and were reported by at least seven observers (5, 10, 14, 23, 38, 45, 53). Such delayed sounds are what one would expect for sonic booms. Most of our reports about this were received from individuals in the Portland metropolitan area. Although these booms occurred long after the fireball, no specific time delay was estimated. One report that did have a specific time delay was received from an observer (45) near Puget Sound, in Belfair, WA. According to this observer, "3 heavy booms" were heard by him 2-3 minutes after the fireball. The three heavy booms probably correspond with the break-up events evidenced by the visual fragmentation record. Taking the speed of sound (dependent on temperature, and thus height in atmosphere) to be ~295-340 m/s (Matson, 2004), this implies observer 45 was located ~35-60 km from these main fragmentation events.

A more equivocal example of delayed sound is provided by observer 16 in the Portland area, who heard a "rumble" or "thunder" sound shortly after seeing the fireball. According to the observer, the rumbles were heard ~12 seconds after seeing the fireball. This short delay would imply close proximity to the fireball, if the sounds heard were the result of shock waves. However, we consider it more likely either that this time estimate is in grave error (much shorter than the actual time delay), or that the sound heard is not the result of a shock wave. In the latter case, the sound could be considered to be "anomalous".

We received four more definite reports of anomalous sounds, those appearing near-simultaneously with the appearance of the fireball, from observers located in Oregon (observers 24, 32, 43, 48). These sounds are anomalous in the sense that they occur too soon relative to the appearance of the fireball to be considered sonic booms. These anomalous sounds have long been reported (possibly as early as by ancient Chinese– Wu and Zhang, 2003) but are somewhat controversial. Although greeted with early skepticism (Heide, 1957, p. 12), they appear to be real (Sears, 1978, p. 29; Pugh, 1989, 1993, 1994). They have been termed "electrophonic" sounds, and explained as a result of an interaction between large fireballs with appropriate objects on or near observers, which transduce audio-frequency electromagnetic radiation into sound waves (e.g., Keay, 1980, 1992; Keay and Ceplecha, 1994). Besides the evidence discussed by Keay (1980, 1992), recent compelling evidence that fireballs create this type of transduction process has been found (Verveer et al., 2000; Price and Blum, 2000). Anomalous sounds seem to be confined to meteoroids over 20 kg in mass, and a nighttime electrophonic fireball is estimated to occur once every 2 or 3 years (Keay and Ceplecha, 1994).

As far as the June 3 fireball is concerned, evidence suggests that it too resulted in anomalous sounds. Observer 26 heard a "rumble" sound ~1/2 second after the flash. Observer 43 heard a "pop" sound ~1 second after the flash. Observer 48 reported a "swishing" sound while seeing the fireball. Observer 24, who was standing next to a cyclone fence at a local airport, commented on hearing a "boom" as the fireball disappeared. Observer 32 was driving over the Columbia River on the I-205 steel bridge when they saw the flash and simultaneously heard a "static, electric sound" and a "clicking" noise. Notably, the observers reporting anomalous sounds were each located in close proximity to metallic structures that could have served as transducers, either in automobiles (observers 26, 43, 48, and 32), next to a metallic fence (24), or on a steel bridge (32). Perhaps not coincidentally, the most sustained and unusual sounds were described by the observer located on the massive steel bridge.

Electromagnetic pulse? The observer (32) on the steel bridge also described another phenomenon. Besides hearing unusual sounds, this observer commented that during the fireball, they "felt static". We suggest that this observer, who volunteered the information without prompting, may have experienced an electromagnetic pulse (EMP) initiated by the fireball, perhaps amplified by the bridge. Another possible example of an EMP effect were the "chills" felt by observer 58 during the fireball, although this could also have been psychological. Fireball-generated EMP pulses are consistent with certain information about previous fireballs, notably the "sharp electric shock" felt by a mechanic up a telegraph pole whose lines were turned off, during the Sikhote-Alin fireball (Krinov, 1966, p. 293)

Smells. Observer 20, in Chehalis, WA, smelled "ozone" shortly after the fireball. Secondhand reports (Edwin Thompson, personal communication) indicate that a policeman, also in Chehalis, smelled "sulfur" shortly after the fireball passage. Sulfurous odor is a common smell reported for fireballs (Sears, 1978, p. 33; Hildebrand et al., 2000), and ozone is known to be produced during electrical discharges (e.g. lightning) in the atmosphere. The ozone smell is consistent with evidence that the fireball may have produced an electromagnetic pulse or an electrical discharge (see above). The reports of smells we received are limited to the Chehalis area, suggesting that the fireball passed in the vicinity of this area. However, during the Tagish Lake fireball, prompt smells were reported up to 100 km from the ground projection of the fireball track (Hildebrand et al., 2000), suggesting that an extremely close passage to Chehalis for the June 3 fireball is not required.

Animal effects. The Pacific Northwest fireball created an impression on human observers, waking many who were sleeping with curtains drawn, but also had an effect on animals. Observer 6 in the Portland area commented that "dogs started barking" and observer 54 in Washington noted that "coyotes started howling" as a result of the fireball. Also in Washington state, the fireball caused "birds to start chirping" (observer 18) at 2:40 am, possibly owing to the immense luminosity it generated.

Trajectory. Although many observers did not get a good look at the fireball itself, some observers got a better view and provided us with qualitative and potentially quantitative information about the trajectory of the fireball. This includes general directions about where the fireball was seen, and more specific information that can be used to estimate azimuths and altitudes for both "first" and "last" sightings of the fireball. In Table 1, we show first and last azimuths in cases where these have been estimated, either by observers, or by us based on details provided the observers. Where only general directions towards the fireball are available, they are shown in Table 1 with quotation marks to clearly indicate their lower degree of specificity.

Early reports received from eyewitnesses, and reported in the news media (e.g., The Chronicle, 2004), suggested that the fireball moved generally west to east, and that it may have passed close to but north of the Chehalis area. This general conclusion is consistent with later reports we received indicating that the fireball appeared northwards of Chehalis (observer 19), and southwards of Olympia (observer 14) as it moved eastward (Table 1). Only 3 reports we received are inconsistent with this general conclusion.

Observer 49 in southwest Portland claimed to see the fireball in the southwest, clearly in error. Observer 45 in the Puget Sound area, north of Olympia, first saw the fireball high overhead (estimated altitude of 80E) and eastward (estimated azimuth of 80E) before watching it move lower in the sky towards due east (Table 1). If this observer estimated correctly, it would indicate that the fireball moved northwards of Olympia, apparently inconsistent with observer 14 and with a more southerly location closer to Chehalis. However, we note that accurate determination of azimuths is especially difficult for fireballs close to the zenith, making the azimuth estimate of observer 45 highly suspect. The high altitude estimated by this observer (80E) also is uncertain, as it apparently conflicts with an "early-seen" altitude of ~60E (almost in the opposite direction) estimated by the Olympia observer. (It is unclear which of the altitudes from observers 14 and 45 are in error, if not both, but fairly certain that they both cannot be correct.) Finally, we received a report from an observer (59) in central Washington, who saw the fireball as he was looking behind and to the left in the driver's side window of his truck, while driving in an apparently eastward direction. This would also place the fireball too far to the north to be consistent with our other reports. This discrepancy would be obviated if the trucker was moving on a more northeasterly course, as opposed to due east as he believed. Aside from these three reports, most of the data we obtained on fireball position suggest a more southerly track. We will return to this point later in connection during discussion of seismic reports, which imply a more northerly track (Tatum, 2004, Matson, 2004).

By far the most challenging aspect of our analysis was the effort to use the most specific eyewitness accounts to determine a trajectory of the fireball. We found that we could not rely on initial observer estimates of the altitudes and azimuths, without receiving additional information that allowed us to refine estimates. The most specific estimates obtained by observers were based on landmarks, but in most cases the assumption made by the observers as to the azimuth of these landmarks, and consequently of the fireball, was in error. Upon further questioning of observers, by looking up features on maps, or by using a compass at observation locations, we were able to obtain a set of what we considered to be more reliable estimates of azimuths and altitudes. These data were used for a trajectory analysis and are indicated by asterisks in Table 1. Fortunately, these most reliable reports cover a large geographic area, allowing the possibility for a successful triangulation.

Fig. 3 shows sighting lines for "initial" and "last" appearance of the fireball based on the most reliable reports, using the same base map as in Fig. 2. (This base map corresponds to the AAA 2004 Edition map which uses a Lambert Conformal conic projection. Slight curvatures of sight lines over large distances are neglected in Fig. 3, but were taken into account during the triangulation solution.) If all observers saw the fireball at the exact same moment and obtained accurate estimates of azimuths, each set of sighting lines would converge on a specific point for the initial and last appearances. Clearly, this does not occur. However, the early and late fireball sightlines do approximately converge, with early sightings concentrated at a point east of Chehalis, WA, and late sightings concentrated near Randle, WA (Fig. 3). This implies that the fireball was seen to move in a generally southeastward direction, from east of Chehalis towards Randle.

One can obtain a quantitative estimate of geographic location of the initial and last fireball locations by averaging all of the intersection points produced by any pair of sightlines. Estimates of the apparent height can be obtained from trigonometric calculation using altitude angles and the distance to the triangulation point. The standard deviation of the averages can be used to gauge the uncertainty in both geographic position and height. Table 2 summarizes geographic coordinates and apparent heights of the initial and last triangulation positions. Two solutions for the initial position are indicated in Table 2, depending on whether the most northerly intersection of early sightlines in Fig. 3 is included or not. This northernmost intersection point is somewhat of an outlier, indicating it may not be valid. Although we believe that the best estimate excludes this northern outlier, including it does not significantly affect our conclusions, other than to change the apparent bearing of the meteor by several degrees (Table

2).

Our analysis suggests that the fireball was first well seen at -122.48E ± 0.11E longitude and 46.69E ± 0.14E latitude at a height of 148 ± 41 km. This initial triangulation point is centered ~22 km north of Cinebar, WA, with an uncertainty (1 standard deviation) of roughly ± 9-16 km. It was last seen near -121.93E ± 0.20E longitude and 46.41E ± 0.17E latitude at a height of 33 ± 8 km. This last triangulation point is centered ~14 km southeast of Randle, WA, with an uncertainty of roughly ± 16-19 km. These errors are much larger than errors caused by neglecting the effect of the curvature of the Earth, or by any operator errors in triangulating. The non-linear dispersal of the triangulation points (Fig. 3) suggest that the errors do not entirely reflect differences in the times that the observations were made, although some error caused by this effect would be expected. Instead, the errors mainly reflect the inherent inaccuracy of the azimuth estimates.

Fig. 3 shows the best estimate of the fireball track between the first and last sighting positions. Two tracks are shown,1 and 2, depending on whether the northernmost early traingulation point is included (track 1) or not (track 2). Combining the best estimates of the initial and last positions of the fireball using track 2 allows an estimate to be obtained for its bearing (~122E) and descent angle (~ 65E) (Table 2). Within the errors inherent in our dataset, these values agree with estimates based on the video recording of the fireball obtained by the Courtenay, British Columbia all sky camera. Based on this recording, the fireball is reported to have a bearing of ~114.5E, and a descent angle of ~51E (Langbroek, 2004).

If the fireball track we determined corresponds to the ~4 second duration inferred for the fireball (see above), this would imply an average speed for the fireball over this portion of Washington of ~32 km/s. This is faster than assumed by Langbroek (2004). However, such a fast speed is consistent with his suggestion that the fireball may have originated as a cometary body.

Most likely, observers did not see the fireball at the first instant it became visible, but slightly afterwards as their attention was drawn to it. This would indicate that the fireball could have first appeared up-range, to the northwest of the first triangulation position near Cinebar. Qualitative observations suggest that the meteor passed over interstate I-5 between Chehalis and Olympia. If one extends tracks 1 and 2 up-range from the early sighting point, they are indeed seen to pass over interstate I-5 between Olympia and Chehalis, either ~5 km south of Olympia (track 1), or ~13 km south of Olympia (track 2) (Fig. 3). Extrapolating the apparent trajectory backwards and keeping the angle of descent constant at ~65E, the apparent height of the fireball above I-5 would have been ~200 km, which seems rather high to be visible as a meteor. Moreover, this appears to be too high to be consistent with the sonic boom delay noted by observer 45 in Belfair (see above). This could indicate either that the trajectory of the meteor steepened as it entered the atmosphere, or that the height of the meteor at the first triangulation point was on the lower end of the range estimated above (i.e. closer to ~100 km than to ~150 km). If an apparent height of 100 km is assumed at the first triangulation point, the angle of descent of the fireball becomes 51E, in exact agreement with the value quoted by Langbroek (2004). This lower height over the early triangulation position also becomes consistent with the sonic boom delay noted by observer 45, especially if the delay were closer to the 3 minute limit estimated by the observer.

Considering the terminal end of the fireball, Fig. 3 shows error ellipses centered on the last triangulation, whose radii correspond to ±1 and ±2 standard deviations (σ) for the best fit solution. Assuming that the dispersion in triangulation points is caused by random error, as seems likely, the ellipses in Fig. 3 can be interpreted as ~68% and ~98% confidence limits. Thus, one can say that to within ~68% confidence, the fireball was last triangulated in a region extending from Randle to the south-southeast (Fig. 3). To within ~98% confidence, the last triangulation occurred in a region extending from the southern boundary of Mt. Ranier National Park, to the northwest boundary of the Mt. Adams wilderness, and encompassing much of Mt. St. Helens National Monument (Fig. 3).

Assuming that unseen meteorites would have continued to fall downrange of the last triangulation point at angles comparable to or slightly steeper than the angle of fireball descent (60-70E), the error ellipses can be shifted ~10-20 km downrange to yield the location expected for meteorites. A 75E to 60E angle of descent would move the center of the ellipses in Fig. 3 to points A and B, respectively. The ellipses for meteorite recovery would move closer to, and overlap with, the Mt. Adams wilderness, and would move away from Mt. St Helens and begin to overlap the Goat Rocks Wilderness area. This area is heavily forested, mainly roadless, and virtually unpopulated, which would seem to make recovery of meteorites from the June 3 fireball highly improbable (but see below).

Ground zero: between Randle and Packwood? Although the data do not permit a more specific quantitative assessment of the last location of the fireball, qualitative observations by the observers closest to the apparent fireball endpoint provide an indication that the fireball may have extinguished in the area between Randle and Packwood, WA. Observer 56 in Randle caught a glimpse (~1 second long) of the fireball, generally northwards. This observer reported the fireball moving left to right but also downwards at a 90E angle, and further suggested that the fireball disappeared in trees at an altitude of ~0E. These somewhat contradictory statements are difficult to reconcile, but it seems fairly certain that observer 56 saw the fireball on the north side of highway 12, which passes east-west through town. Observer 60 in Packwood saw the fireball on the same side of highway 12, but the highway there has a more northerly bearing, almost at right angles to its bearing through Randle. This suggests that the last extinction point of the fireball was actually in the area between Randle and Packwood, roughly over Purcell Mountain (elevation 5,542 feet). This area is well within the 2σ error ellipse and just outside the 1σ error ellipse for the last triangulation point estimated above (Fig. 3). Taking 10-20 km downrange of this position to be the most likely place to recover meteorites, we suggest that meteorites could have fallen somewhere in the vicinity of highway 12 between Randle and Packwood, or to the southeast towards the western boundary of the Goat Rocks Wilderness area. It is ironic that meteorites could have fallen on highway 12, the main route through "ground zero", in an otherwise unpaved roadless area.

Inconsistency with seismic data. Our inferred trajectory is inconsistent with seismic data which suggest a terminal burst position of the fireball over the Snohomish, WA area (Tatum, 2004; Matson, 2004). The June 3 fireball generated sound waves that were recorded by various seismic stations in British Columbia and Washington state, and these were modelled to obtain a position of the terminal burst, assuming either an isothermal (Tatum, 2004) or non-isothermal (Matson, 2004) atmosphere.

The coordinates derived for the isothermal model (using seismic data from stations in British Columbia) were -122.08E longitude and 47.83E latitude, with a poorly-defined height of 20 km (Tatum, 2004). Those for the non-isothermal model (using data from stations in Washington) were -121.978E longitude, 47.971E latitude, and a height of 38.7 km (Matson, 2004). These height and longitude values agree within error with our values for the last triangulation point (Table 2). However, the latitude values obtained from seismic data are ~1.6E further to the north, far outside our expected range of uncertainty (Table 2). Indeed, the Snohomish location appears inconsistent with even qualitative eyewitness accounts of the fireball track. Among all of the reports we received, only one (from observer 59) is possibly consistent with the fireball being located at low heights above Snohomish. Our most northerly observer (45), located in the Puget Sound area, estimated the fireball to be located due east when it disappeared, which would place it ~50 km to the south of Snohomish. As discussed above, we believe that the azimuth estimated by this observer could easily be in error, and most likely the fireball passed even more to the south. Clearly, the visual reports are inconsistent with the seismic-derived locations for a terminal burst.

The reason for this discrepancy is unclear at this time. One possibility is that the key assumption in the seismic models of a single point source for the origin of the sound waves is in error. Visual observations indicate that the fireball experienced multiple fragmentation events, each of which could have generated sound waves. Indeed, multiple sonic booms were often heard by observers. For example, at least three heavy booms were noted by observer 45 in Belfair, closest of our observers to Snohomish, and "rumbles" were heard by others (Table 1) . Thus, instead of a single point source, the fireball is likely to have produced multiple point sources of sound waves originating along the fireball track. As the fireball was moving through a non-isothermal atmosphere with a strong temperature gradient, it is even conceivable that sound waves generated at different times along the fireball track could intersect, resulting in a complex situation that could be difficult to model. We note that for the Tagish Lake fireball, ground- shaking sonic boom detonations were also recorded by seismographs, but that these were difficult to interpret (Hildebrand et al., 2000) in light of the known trajectory. Whether a multiple-fragmentation and multiple-boom process can explain the discrepancy between seismic and eyewitness data is uncertain, and a good topic for further research.

CONCLUSIONS

Analysis of eyewitness data for the June 3, 2004 fireball over the Pacific Northwest suggests the following: (1) Scientifically useful information can be derived regarding fireballs even from untrained and surprised members of the public. The most difficult analysis concerns estimates of trajectory. In general, azimuths and altitudes estimated by the public cannot be trusted, although in some cases, apparently more accurate information can be obtained upon further questioning. (2) The duration of the fireball was estimated by observers to vary anywhere between 1-6 seconds, leading to our best estimate of ~4 seconds, in agreement with a video recording. (3) The data strongly support the idea that the fireball experienced multiple fragmentation events, breaking into three main pieces that themselves fragmented. If the fireball produced meteorites, as seems likely, it should have resulted in a strewn field. (4) The data provide further support for the idea that large fireballs can create anomalous or electrophonic sounds as a result of an electromagnetic effect. Some evidence for an electromagnetic pulse was also found. (5) The fireball appears to have moved generally from northwest to southeast, crossing over interstate I-5 between Olympia and Chehalis. Using the most reliable and specific estimates of altitudes and azimuths, we modelled the trajectory of the fireball. The fireball appears to have been tracked from near the towns of Cinebar to Randle, WA. The bearing was ~122E and the descent angle was ~ 65E, although a somewhat less steep descent angle seems more reasonable. Both of these parameters are consistent with a video recording. (6) The trajectory we derived is inconsistent with seismic data suggesting a much more northerly track for the fireball. The reasons for this discrepancy are unclear, but it could indicate that the assumption of a single point source for sound waves generated by this fireball is not valid. (7) We suggest that "ground zero" for meteorite recovery is near highway 12 between the towns of Randle and Packwood, or towards the southeast in heavily timbered country towards the western edge of Goat Rocks Wilderness.

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Table 1. Fireball field data. Az/alt = azimuth/altitude (in degrees); #1 and #2 refer to “first” and “last” observation, respectively. Color changes indicated by arrows. Asterisked records indicate data used for triangulation of fireball trajectory.

Observer	Location	Az/alt #1	Az/alt #2	Descent Angle	Color	Fragments	Sound	Comment
1	Sandy, OR	“north”			orange flash			
2	Brooks, OR	325/45		60	white			
3	13 km E Toutle, WA				white flash			
4	Sweet Home, OR	“north”			yellow flash			
5	I-5 bridge, Columbia River	“north”			green flash		1 boom	
6	Damascus, OR	“north”		90	yellow orange			6
7	Hazeldell, WA	“northwest”	“north”	60	white ± red ± green			
8	Bend, OR				blue flash			
9	Boardman, OR	“northwest”		90	white green			
10	SE Portland, OR	“north”		30	yellow orange		rumble	
11	Hazeldell, WA	~315/45	~0/10	45	red			
12	Beaverton, OR	~25/			white			12
13	24 km E Goldendale, WA	340/10		90	yellow orange flash			
14	Olympia, WA	200/60	/0	90	orange		rumble	14
15	Vancouver, WA	315/60	60/0	45	yellow green			
16	SW Portland, OR				pink		thunder	16
17	SW Portland, OR				2 white flashes			
18	Hazeldell, WA	“northeast”		70	yellow ± orange ± red			18
19	Chehalis, WA	“north”		45	white, double pulse			19
20*	2 km S Chehalis, WA	56/	116/	90	white ± orange	yes		20
21*	E Portland, OR		30/	80	yellow	12		21
22	Rainier, OR				white			
23	SW Portland, OR						boom, then rumble	
24	Hillsboro, OR	“north”		45	blue green		anomalous	24

Table 1 continued on next page.

Table 1, cont.

Observer	Location	Az/alt #1	Az/alt #2	Descent Angle	Color	Fragments	Sound	Comment
25	16 km NE Packwood, WA				white, double pulse			25
26	Beaverton, OR		“north”	45	yellow ± green ± blue	4	anomalous	26
27	Woodland, WA	70/45	90/20	45	orange			27
28*	4 km E Rufus, OR	307/45	317/15	90	green			28
29	SE Portland, OR	~20/	~20/	90	orange			29
30	NE Portland, OR	~45/	~45/	90	red			
31	Tigard, OR		“north”			white flash		
32	Vancouver, WA		“northeast”		white		anomalous	32
33	18 km N Battleground, WA	30/60	50/45	70	yellow	5-6		
34	Sandy, OR		“north”		white flash			
35	NW Portland, OR				white flash			35
36	Toledo, WA	90/30		60	red yellow	“sparks”		
37	3 km E Elgin, OR	30/60	45/10	45	yellow orange	2		
38	Camas, WA						heavy boom	38
39	Beaverton, OR	330/60	0/0	80	red ± yellow ± blue			
40	N Portland, OR	315/45	0/10	35	white			
41	Tigard, OR	12/45	/20		80	white yellow		
42	NE Portland, OR	330/60	45/10	35	yellow white			
43	Portland, OR	30/45		90	orange		anomalous	43
44	NE Portland, OR	15/60	/10	80	red ± orange ± white	“sparks”		
45	Belfair, WA	80/80	90/45	35	orange red	7	3 heavy booms	45
46	Longbeach, WA		“northeast”		purple white			
47	Spokane, WA				white			
48	Goble, OR	0/90	90/20	45	white orange		anomalous	48
49	SW Portland, OR		“southwest”				white	
50	Woodburn, OR	270/30		45	yellow	4-5		

Table 1 continued on next page.

Table 1, concluded.

Observer	Location	Az/alt #1	Az/alt #2	Descent Angle	Color	Fragments	Sound	Comment
51	Salem, OR	0/		45	orange green			
52*	St. Helens, OR	22/45	52/20		white ± yellow ± red			52
53	Milwaukie, OR				white		1 boom	53
54	10 km S Tenino, WA				white			54
55	Forest, WA	90/			white flash			
56	Randle, WA	"north"		90	white			56
57*	5 km E Corbett, OR	355/50	5/20	45	white ± red ± orange	5-7		57
58*	5 km E Corbett, OR	350/50	10/15	40	white	5-6		58
59	Kittitas, WA	~290/						59
60	Packwood, WA		305/					60

Comments: 6– Caused dogs to start barking. 12– Two pulses of light. 14-- Observer was moving along I-5 southbound and saw fireball ahead. 16-- rumble heard ~12 seconds after fireball. 18– Birds started singing. 19– Observer was moving northbound on I-5 and saw fireball ahead. 20– Smelled ozone. Azimuths estimated relative to I-5 southbound, taken to have bearing of 136E. First sighting 10E to south of lefthand perpendicular to I-5. Fireball moved 60E in apparent azimuth clockwise. 21-- Compass used by CML personnel to estimate azimuth. 24– Boom heard "just as fireball disappeared". Observer was standing next to metal cyclone fence at Hillsboro airport. 25-- Observer did not provide azimuths but suggested fireball seen east of Mt. Ranier. 26– "Rumble ½ second after flash". 27-- Bearings estimated by observer using landmarks and map. 28– Observer at southwest corner of John Day dam. Azimuths estimated relative to orientation of dam, taken to have bearing of 322E. First azimuth was "one fist" (10E) to left of dam and last was "one-half a fist" (5E) to left of dam. Observer reported "flash after [meteor] went below hill". 29– Awakened by flash. 32– Observer on I-205 steel bridge. Heard "static electric sound" and "clicking". "Felt static." 35-- Observer saw "white flash behind Cascades" generally eastward. 38-- Dog awoke. 43– "Pop" sound during fireball or 1 second after. 45– Three heavy booms 2-3 minutes after fireball. 48– "Swishing" sound during fireball. 52-- Azimuths determined relative to northbound highway 30, estimated to have bearing of 37E. 53-- Awakened by flash. 54-- Coyotes started howling. 56-- fireball seen to move "left to right" facing north. 57-- Observer #1 at Crown Point. Bearings measured by CML personnel with compass. Estimated accuracy of ±5E in azimuth and altitude. 58– Observer #2 at Crown Point. Bearings measured by by CML personnel with compass. Estimated accuracy of ±5E in azimuth and altitude. Observer felt "chills". 59-- Azimuth estimated relative to road. Smoke trail across sky. 60-- Fireball seen to move below treeline. Azimuth determined relative to highway 12, taken to have bearing of 5E.

Table 2. Triangulation positions and heights for "first" (or early) and "last" observations for two possible tracks to the June 3, 2004 fireball. N= number of observations averaged. Errors represent ±1 standard deviation of the average. Apparent heights to triangulation points were determined separately for each observer before averaging. Track 2 is considered more likely. Apparent heights for the first observation may be overestimated (see Text). The last observation excludes from the average three potential triangulation points created by the intersection of sightlines between observers 20/28, 21/57, and 21/58, which lie only ~25-35 km north of the Columbia River, an unrealistically southern position for the fireball.

	First observation	First observation	Last observation
	Track 1	Track 2	Tracks 1 & 2
Longitude	-122.44E ± 0.16E (N=9)	-122.48E ± 0.11E (N=8)	-121.93E ± 0.20E (N=11)
Latitude	46.72E ± 0.17E (N= 9)	46.69E ± 0.14E (N= 8)	46.41E ± 0.17E (N= 11)
Apparent height (km)	148 ± 40 (N=14)	148 ± 41 (N=13)	33 ± 8 (N=14)

Track 1 bearing: towards ~141E. Track 1 descent angle (from horizontal): ~65E.
Track 2 bearing: towards ~122E. Track 2 descent angle (from horizontal): ~65E.

FIGURE CAPTIONS

Fig. 1. Fireball report form used by CML personnel. This form is available on-line at http://meteorites.pdx.edu/CML_Fireball_form.htm

Fig. 2. Map showing the locations of eyewitnesses to the June 3, 2004 fireball in the area between Portland, OR, and Seattle, WA including the interstate I-5 corridor and Cascade Range. Eyewitnesses lying outside this map area include observers 2, 4, 8, 9, 46, 47, 50, and 51. Base map: AAA 2004 Edition, State Series Oregon/Washington.

Fig. 3. Map of same area as Fig. 2 showing first and last sighting lines (orange and blue, respectively) used for trajectory analysis, and two possible fireball racks (green) derived from these data. The red ellipses show the 1σ and 2σ uncertainty areas (~68% and ~98% confidence locations, respectively) for the final sighting location. Points A and B correspond to the centers of meteorite-recovery ellipses shifted downrange from the final sighting location assuming a 75E and 60E descent angle, respectively, for the terminal (unseen) descent of meteorites.

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Cascadia Meteorite Laboratory / Portland State University

Fig. 1: Fireball Report Form

Your Name, Address & Phone ____

____

Observation Date: ______________________ Local Time: ______________________

Observer's Name: ____

Address: ____

Phone Number: Home (________) ______________________Work (_________) ______________________

Observation Site: ______________________________________ In Car? ___________

Direction Observer Was Facing: ______________________ Fireball Moved: L to R ________ R to L ________

Path: Parallel to Horizon ______ Overhead ______ Straight Down ______ Downward at some angle __________

____

First Sighting: Azimuth ______________________ Altitude ______________________

Last Sighting: Azimuth ______________________ Altitude ______________________

Duration (seconds): ___________ Apparent Velocity: Fast _____ Medium _____ Slow _____ Not Moving ______

Brightness: Too Bright to Look at __________ Brighter than __________ or as Bright as Full Moon ___________

Brighter Than _________ or as Bright as Venus _________ Objects cast shadows ______________

Diameter Compared to Full Moon: ____

Color: ______________________ Shape: ______________________

Change in Brightness and/or Color and/or Shape: ______________________________________

Trail: Sparks ______________ Smoke ______________ Length _______________ Duration _________________

Termination: Flared Brightly _______ Fragmented _________ (Number of Fragments ______________________)

Passed out of view while still bright _________ (in clouds ______________ in trees _________________

Behind Building _________ Below Horizon ______________) Vanished above Horizon _______________

Sounds Heard : With fireball _________ After termination _________ (how long after? _____________________)

What sorts of sound? ____

Did you feel or experience any kind of strange sensation? ______________________________________

____

Comments and Sketches: Use back of report form.

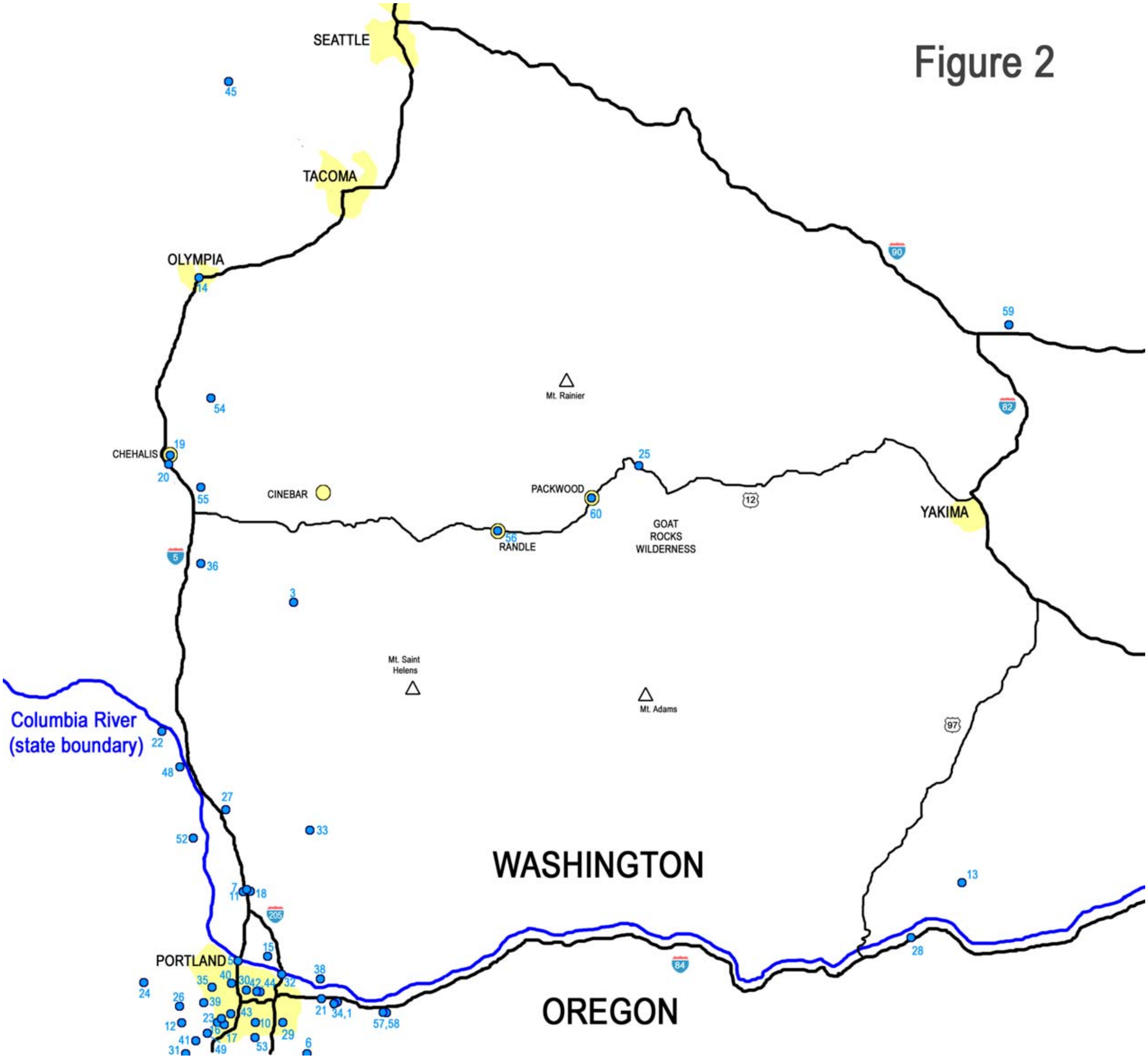
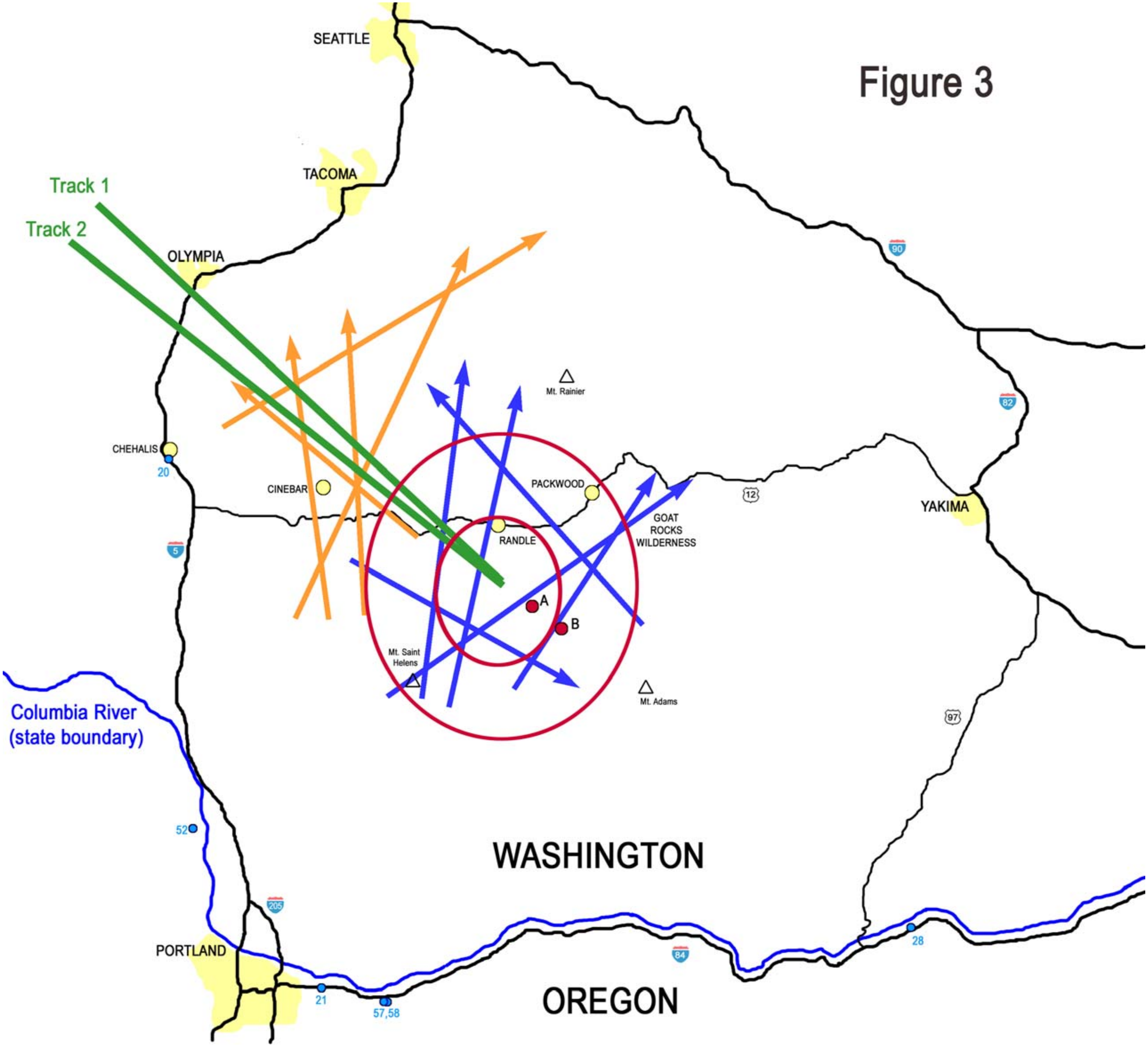

SEATTLE
TACOMA
OLYMPIA
CHEHALIS
CINEBAR
PACKWOOD
RANDLE
GOAT
ROCKS
WILDERNESS
YAKIMA
Mt. Rainier
Mt. Saint
Helens
Mt. Adams
Columbia River
(state boundary)
PORTLAND
WASHINGTON
OREGON
90
82
5
12
97
205
84

Figure 2

Figure 3


SEATTLE
TACOMA
Track 1
Track 2
OLYMPIA
90
Mt. Rainier
82
CHEHALIS
20
CINEBAR
PACKWOOD
12
YAKIMA
GOAT
ROCKS
WILDERNESS
RANDLE
5
A
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Mt. Saint
Helens
Mt. Adams
97
Columbia River
(state boundary)
52
WASHINGTON
205
PORTLAND
84
28
21
57,58
OREGON