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PERLITE MINING AND RECLAMATION IN THE NO AGUA PEAKS, TAOS COUNTY, NEW MEXICO

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Abstract—Perlite mining is an important extraction industry in New Mexico and the United States as a whole. In 2010, there were nine operating perlite mines owned by seven companies in six western states, with New Mexico leading the United States in perlite production. Over 375,000 metric tons of perlite were reported to have been produced in the United States in 2010, with an estimated ore value of $19.6 million. Currently there are three permitted and operating perlite mines in New Mexico: two in Taos County and one in Socorro County. Perlite is mined in Taos County at No Agua Peaks, an approximate 6.5 km^2 area of rhyolitic domes among a succession of late Cenozoic volcanic and sedimentary rocks that overlie the Precambrian metamorphic and igneous rocks along the west side of the Taos Plateau. The New Mexico Energy, Minerals and Natural Resources Department's (EMNRD) Mining and Minerals Division (MMD) regulates, permits and oversees mineral extraction activities, and requires reclamation to a defined post-mining land use. Contemporaneous reclamation of a fine perlite dump (mill reject material) at the El Grande Mine, operated by Dicaperl Mineral Corporation, consisted of re-contouring, stabilization, control of surface water runoff, covering of waste material with a suitable growth media, and seeding to promote re-vegetation. On-going test plot studies to monitor revegetation success and develop new reclamation techniques are being conducted at the No Agua Mine, operated by Harborlite Corporation, in preparation of final or contemporaneous reclamation.

INTRODUCTION

Perlite is a term that has dual meaning. In geologic terms, perlite is an altered, hydrated (2-5 wt. % water) volcanic glass, generally of a high silica (75-77.5 wt. %) rhyolitic composition, that is formed by the rapid cooling of viscous, high-silica rhyolite lava flows and/or lava domes. In industrial terms, perlite is a lightweight, anhydrous glass that is produced from the rapid expansion of the glass ("popping") upon heating above 1600°F, causing a marked volume increase of up to 20 times its original volume (McLemore and Mullen, 2004; Chamberlin and Barker, 1996). Occurrences of perlite worldwide are associated with Tertiary through middle Quaternary continental volcanic fields (Barker et al., 1996).

New Mexico has several known, commercially viable perlite ore deposits: a world-class deposit in the No Agua Peaks in west Taos County (Fig. 1), a high-yield deposit in Socorro County, a small to moderate deposit in Grant County, and a small to moderate deposit in Cibola County. While perlite can occur as dikes, single domes, composite domes, sills or flows, economic deposits of perlite typically only occur as single or composite domes of several hundred feet in height, which is the case for No Agua Peaks. New Mexico is reported to be the major perlite producing state within the United States (USGS, 2010). This paper focuses on domestic and international perlite production statistics, the geology of the No Agua Peaks, and mine reclamation activities overseen by the New Mexico Energy, Minerals and Natural Resources Department (EMNRD) Mining and Minerals Division (MMD) at the El Grande Mine and No Agua Mine.

PERLITE USES

Expanded perlite offers several advantageous characteristics for industrial and commercial use including low bulk density, low thermal conductivity, high heat resistance, low sound transmission, large surface area of individual particles, and chemical inertness (Naert et al., 1980). Figure 2 summarizes the various end uses of expanded perlite, with the "formed products" category comprising about 60% of the market. Formed products include construction-related items such as acoustic ceiling tiles, insulation boards, lightweight plaster, lightweight aggregate, pipe insulation, and roof insulation board. Most companies produce more than one size of crude perlite, resulting in various sizes of expanded perlite (Barker et al., 1996). Coarse grades of expanded perlite are typically used as a horticultural additive, including use as a fertilizer, insecticide or chemical carrier, and as an agent to loosen heavy soils and provide a good root base. The medium sizes of expanded perlite are typically used in aggregate and building products. The finest sizes are primarily used in the filtra-

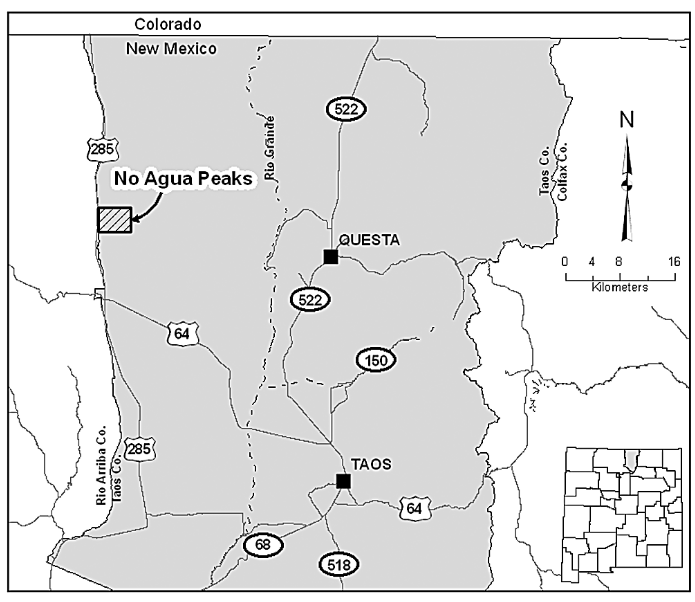

FIGURE 1: Location of No Agua Peaks, Taos County, New Mexico.

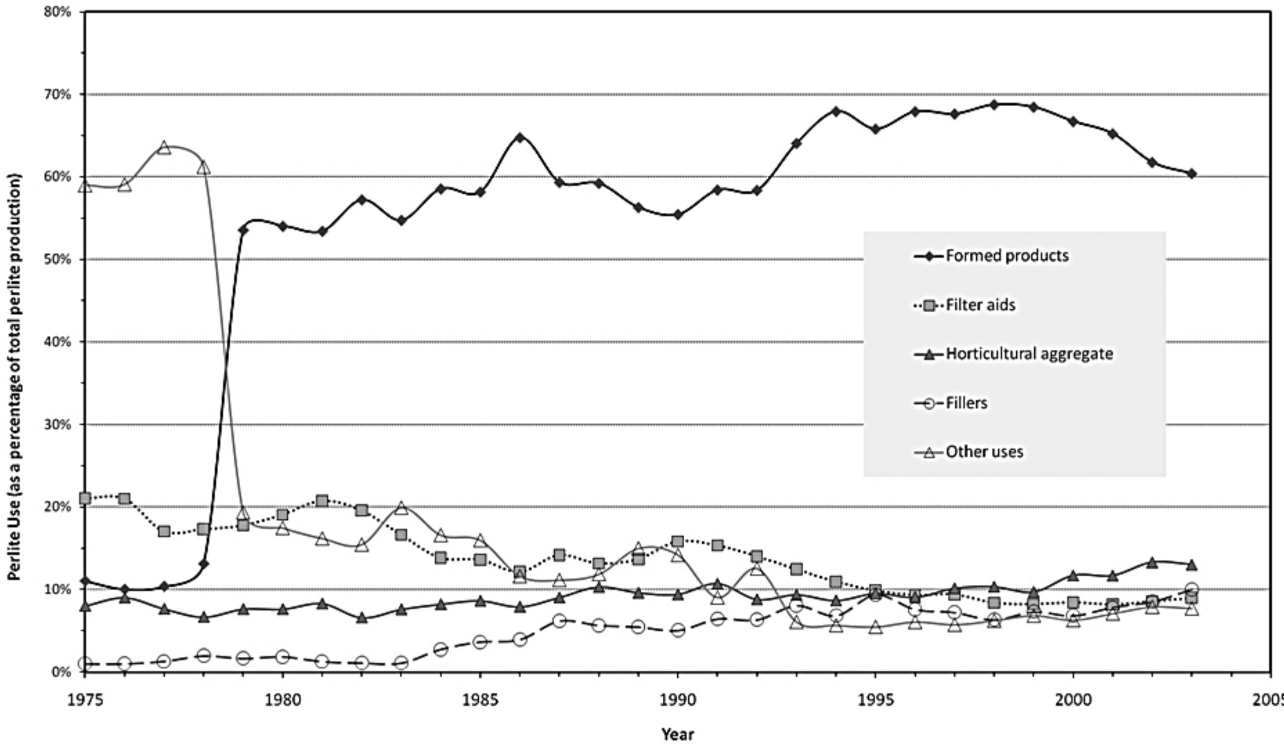

FIGURE 2: End uses of expanded perlite expressed as a percentage of total expanded perlite production (USGS, 2008).

tion of pharmaceuticals, waste water effluent, and other liquids. The "other uses" category for expanded perlite includes use in explosives, high-temperature insulation, paint texturizer, soap, steel, and sugar manufacturing.

DOMESTIC PERLITE PRODUCTION

Domestic perlite ore production began in the 1940's, and generally increased until about 1999 with a peak perlite production of approximately 700,000 metric tons. As of 2008, the most recent data available, domestic perlite ore production was estimated to be approximately 434,000 metric tons (USGS, 2011; Fig. 3). In the United States, perlite ore deposits are confined to the western states; New Mexico leads in ore production with Arizona, California, Nevada, Idaho, and Colorado following. In New Mexico, perlite ore is extracted using open pit mining techniques, where overburden is removed via blasting and/or heavy equipment (i.e., scrapers and rippers) until the ore zone is reached. Once extracted, perlite ore is crushed at a mill, dried, re-crushed and screened to generate various sizes of raw perlite ore. Perlite expansion is typically performed at plants in Canada and Mexico (Barker et al., 1996), although some perlite expansion does occur in the United States.

INTERNATIONAL PERLITE PRODUCTION

Internationally, four countries are estimated by USGS to produce approximately 80% of the world's perlite: Greece, United States, Turkey and Japan. While the United States is reported to have some of the largest perlite deposits in the world, Greece surpassed the United States in perlite production beginning in 2003 (Fig. 4). Note that production information for China and several other counties believed to have significant perlite deposits is unavailable, making it unclear whether Greece and the United States are the world's leading producers (USGS, 2011).

GEOLOGY OF THE NO AQUA PEAKS

Tectonic Setting

The No Agua Peaks consist of two erosional remnants of rhyolite domes and associated volcanic rocks that cover approximate 6.5 km^2 and are located at the intersection of the northeast-trending Jemez volcanic lineament, a trend of episodic basaltic-to-rhyolitic volcanism for the past 10 million years, and the Rio Grande rift valley (Barker et al., 1996; Chamberlin and Barker, 1996; McLemore and Mullen, 2004). The No Agua Peaks are one of approximately 35 central-vent volcanic shields and cones, with compositions ranging from basalt to silicic rhyolites, in the Taos Plateau volcanic field physiographic province (Lipman and Mehnert, 1979). The No Agua Peaks are the volcanic expression of a combination of continental drift over the East Pacific Rise and upwelling in the upper mantle. Upwelling led to increasing extension of the continental crust in middle to late Cenozoic time, and was followed by episodes of gravitational collapse and discontinuous spreading of the continental crust (Chamberlin and Barker, 1996). Isotopic cooling ($^{40}Ar/^{39}Ar$) age data presented in Chamberlin and Barker (1996) indicates that the perlite deposits of the No Agua Peaks were erupted contemporaneously with the latter episode of rifting in late Miocene to Pleistocene time.

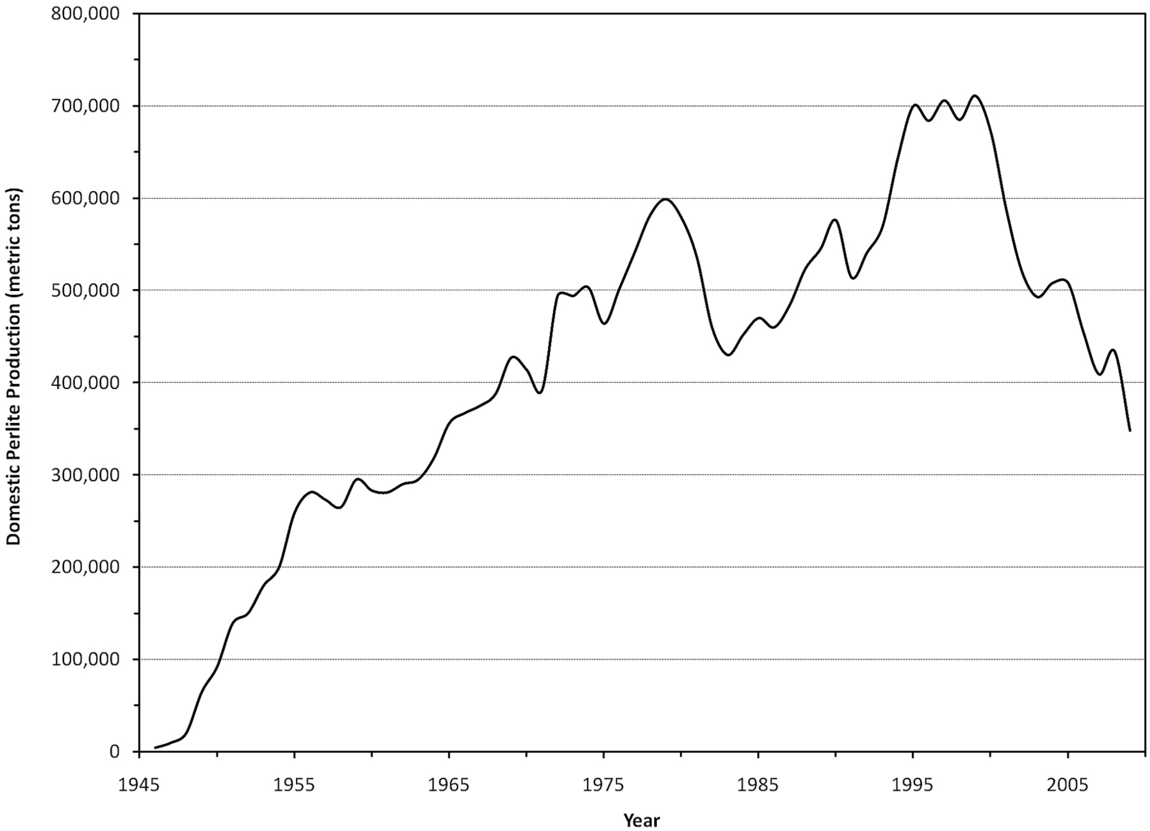

FIGURE 3: Estimated domestic perlite production (USGS, 2011).

One of the common characteristics of high-silica rhyolite flows is that they are emplaced in active tectonic belts, and are therefore subject to numerous destructive geologic processes that contribute to the relative rarity of commercially viable perlite deposits. These processes include erosion, burial by younger volcanic rocks or sedimentary deposits, dissection by faulting, and hydrothermal alteration. Chamberlin and Barker (1996) note that the volcano responsible for the No Agua peaks was emplaced in a favorable structural zone at the western edge of the east-tilted San Luis Basin, which has kept the destructive geologic forces mentioned above to a minimum.

Eruptive History and Model

The No Agua Peaks consist of a series of silicic and intermediate volcanic rocks (Fig. 5). The highest perlite producing deposits in New Mexico, including the No Agua Peaks, are high-silica rhyolite lava flows (75-77.5 wt.% silica), which favor the development of thick glassy zones across the rapidly chilled tops of slowly extruded flows, due to their high viscosity. The No Agua Peaks, with an age of approximately 4.06±0.05 Ma (Appelt, 1998), represent one of the older volcanic centers that collectively make up the Taos Plateau volcanic field, which was erupted between about 5.88 and 1.03 Ma (Appelt, 1998).

Chamberlin and Barker (1996) provide a detailed description of the various eruptive interpretations of the No Agua volcano. Previous researchers have recognized the existence of geochemi-

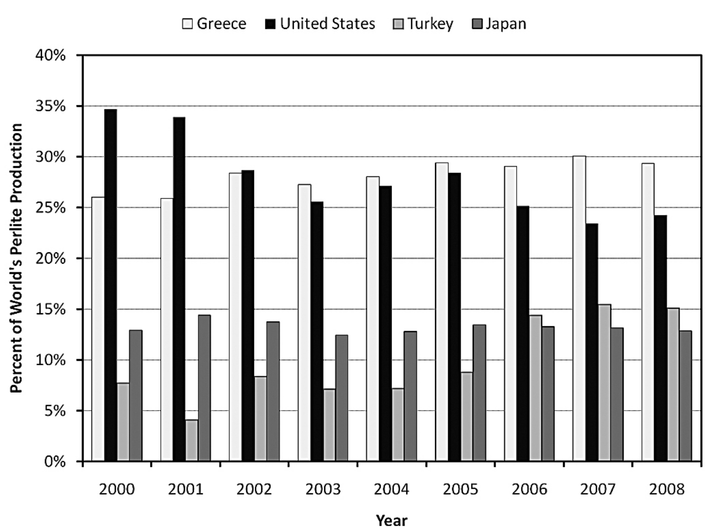

FIGURE 4: Dominant perlite producing countries and their estimated production as a percent of estimated worldwide production (USGS, 2011).

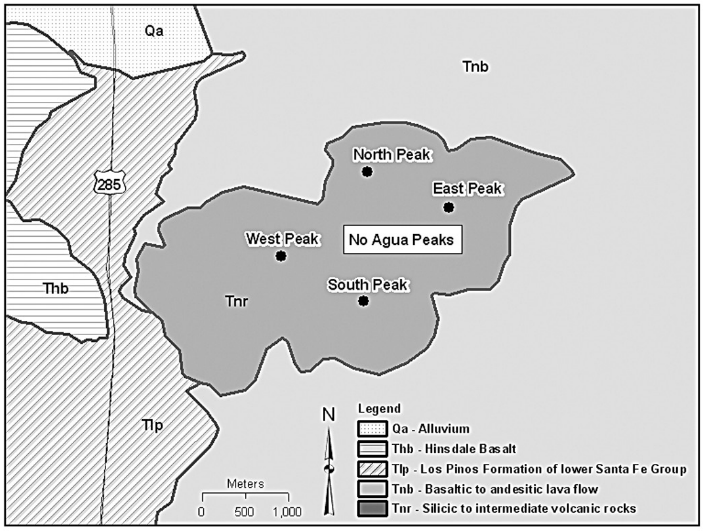

FIGURE 5: Geologic map of the No Agua Peaks (adapted from Geologic Map of New Mexico, New Mexico Bureau of Geology and Mineral Resources, 2003, Scale 1:500,000).

cal differences between the high-silica lavas on the east flank (early phase eruptions) versus the west flank (late phase eruptions) of the No Agua Peaks. Specifically, the high-silica lavas on the east flank of the volcanic center are enriched in barium (Ba) and strontium (Sr), and are depleted in rubidium (Rb), compared to the geochemical signature of the high-silica lavas on the younger west flank. Interpretative models of the No Agua Peaks have changed with additional research. Naert (1974) advocated a four-dome model, as did Lipman and Mehnert (1979), while a two-dome model was reinterpreted by Whitson (1982) and Breese and Barker (1984). The four-dome and two-dome models postulated that the marked geochemical differences observed between the east flank and west flank of the No Agua Peaks are due to the eruption of high-silica lavas from different magma chambers with different geochemical signatures.

Instead, Chamberlin and Barker (1996) reinterpreted the No Agua Peaks as originating from a single, compositionally zoned magma chamber. Chamberlin and Barker (1996), however, concur with previous researchers that the west peak represents a steep-sided lava dome underlain by a central conduit, and further suggest that this is the primary conduit responsible for the entirety of No Agua Peaks, including the older low-Rb, high-Sr lavas of the east flank. In this interpretation, an estimated four phases of eruption occurred:

1. An initial explosive eruption creating a Rb-rich tephra ring around the vent;
2. An early phase eruption of high-Rb silica-rich lava, which created the composite lava dome of the west peak;
3. A middle phase eruption of high-Rb silica-rich lava that was rapidly squeezed out into two lobes from under the west flank of the composite dome, creating the low hills to the west of west peak; and,
4. A late phase eruption of low-Rb silica-rich lava that emanated in three lobes from the northeast flank of the composite dome, which subsequently formed the north peak, east peak and south peak of the No Agua Peaks.

Formation of Perlite

In order for perlite to form, the necessary precursor, obsidian, has to be present. In the No Agua Peaks, obsidian was likely formed by rapid chilling of the surface of the tabular rhyolite lava bodies, followed by slower cooling of the flow interior. In the west peak and low hills area of the No Agua Peaks, obsidian is reported to be locally abundant in vertical lenses (Chamberlin and Barker, 1996; Barker et al., 1996) with the original obsidian content estimated to range from approximately 2% in the composite dome of west peak to approximately 50% in the low hills west of west peak. The original obsidian content of the east flank is estimated to be up to 20% (Chamberlin and Barker, 1996). The estimated perlite resource of the No Agua Peaks follows this same trend: increased original obsidian content equates to increased perlite resource.

Water in obsidian has been documented to range from 0.01 to 1 wt. %, although water content values less than 0.1 wt. % are uncommon. Additionally, the water content in rhyolite flows and domes has been found to rarely exceed 0.5 wt. %, and higher values are only found in intrusive margins of domes, in dikes, or in clasts from pyroclastic deposits (MacDonald et al., 1992). MacDonald et al. (1992) also concluded that rhyolitic glasses with >1 wt. % water content were hydrated with meteoric water, based on various lines of geologic and isotopic evidence.

Chamberlin and Barker (1996) interpret that the perlite in the No Agua Peaks was formed through the secondary process of low-temperature diffusion of meteoric water into nearly anhydrous obsidian. This is supported by oxygen and hydrogen isotope ratios of water extracted from perlite samples collected in the western United States, which show a meteoric origin. As such, the formation of perlite is often viewed as a type of chemical weathering resulting from relatively rapid and uniform bulk hydration through high-initial fracture permeability and interconnected microvesicles (Chamberlin and Barker, 1996). Based on the estimated original obsidian content and perlite resources of the No Agua Peaks, it appears that vesicular high-silica rhyolite lava flows, such as the low hills area, are a more favorable environment for perlite formation compared to large composite, high-silica, crystalline rhyolite lava domes, such as the west peak of the No Agua Peaks.

ENERGY, MINERALS AND NATURAL RESOURCES DEPARTMENT, MINING AND MINERALS DIVISION, MINING ACT RECLAMATION PROGRAM

The New Mexico Energy, Minerals and Natural Resources Department's (EMNRD) Mining and Minerals Division (MMD) consists of four programs, one of which is the Mining Act Reclamation Program (MARP). MARP was established pursuant to the New Mexico Mining Act of 1993 (NMMA) to regulate hardrock mining and reclamation activities. The purposes of the NMMA is to promote responsible utilization and reclamation of lands affected by the exploration, mining and the extraction of minerals. The New Mexico Mining Act Rules (Rules; Title 19, Chapter 10, Parts 1 through 14 of the New Mexico Administrative Code) were promulgated under the authority of the NMMA, and provide the regulatory framework for exploration, underground and surface mining, and reclamation at hardrock mining operations in New Mexico. Where feasible, MMD advocates the operator's use of contemporaneous reclamation during active exploration and mining. Prior to being permitted to perform hardrock exploration and/or mining in New Mexico, the NMMA requires that an operator provide financial assurance for the future reclamation of mining related surface disturbances. Various forms of financial assurance are allowed under the Mining Act Rules including surety bonds, cash deposits, letters of credit, collateral (real estate), and third-party guarantees. At the end of 2010, MMD held over $570 million in financial assurance for on-going exploration and mining activities in New Mexico.

Existing hardrock mines that have created, or will create, greater than 10 acres of unreclaimed mining-related disturbance are regulated under Title 19, Chapter 10, Part 5 of the New Mexico Administrative Code. Mining operations under Part 5 are required to have an approved Closeout Plan that includes a detailed description of how the permit area will be reclaimed to meet various performance and reclamation standards, which, depending on the post-mining land use, may include reclamation to a condition that allows for re-establishment of a self-sustaining ecosystem appropriate for the life zone of the surrounding area following mine closure. Post-mining land use categories include, but are not limited to, cropland, pasture land, grazing land, forestry, residential, industrial/commercial, recreational, and wildlife habitat.

Upon cessation of mining activities, the operator is required to begin reclamation within 180 days from the date of cessation. Once reclamation is completed, the majority of the financial assurance posted by the operator may be released except for the portion necessary for a third party contractor to re-establish vegetation for a period of 12 years after the last year of augmented seeding, fertilizing, or irrigation (unless a post-mining land use is approved by the director of MMD that does not require revegetation).

RECLAMATION IN THE NO AGUA PEAKS

El Grande Mine

The El Grande Mine, owned by Dicaperl Minerals Corporation (DMC), is an active perlite mining and milling operation located on the west peak and low hills on the west flank of the No Agua Peaks. The El Grande Mine was permitted by MMD in 1997 as an existing mining operation. There are various mining-related surface disturbances at the El Grande Mine, totaling approximately 170 acres, associated with buildings, milling equipment, the primary open pit, roads, and miscellaneous waste rock dumps. In 2006, DMC began planning for the reclamation of Dump 1-A, which was no longer needed by DMC. Dump 1-A, located immediately east of the milling facility (Fig. 6), occupies approximately 4.5 acres and is composed of rejected fine perlite from the milling process. Although chemically inert, the fine perlite is highly erodible, and is too finely textured to support appropriate vegetative growth.

Engineering design for the reclamation of Dump 1-A included stormwater control using both earth lined channels (for peak flows with a velocity of <5.0 ft/sec) and riprap lined channels (for peak flows with a velocity >5.0 ft/sec) that were engineered for the 100 yr-24 hr storm event. The channels lead to two sediment ponds engineered for the 10 yr-24 hr storm event, and were sized with additional storage capacity to accommodate 3 yrs of average annual sediment yield at 0% vegetative cover. This was incorporated into the design to account for the potential failure of re-vegetation. Each sediment pond was also installed with a riprap lined spillway capable of passing the peak flow resulting from the 25 yr-24 hr storm. In order to appropriately design a final surface topography for Dump 1-A, a total of eight transects were modeled using the Revised Universal Soil Loss Equation model (RUSLE; Renard et al., 1997). Utilizing a maximum soil loss tolerance of 2 tons/acre/yr, after the establishment of a vegetative cover, RUSLE was employed to help establish final slope lengths and slope steepness of the final cover.

In order to promote sustainable vegetation for the post-mining land use of range management/grazing, which was designated by the operator and approved by MMD, a topdressing with a minimum depth of 12 inches was applied over the reject fines of Dump 1-A. The topdressing consisted of approximately 23,000 cubic yards of Raton complex soil that was previously salvaged by DCM from the pit area, and was stockpiled for future use. Soils analysis of this material revealed it to be approximately 32-52% coarse fragments. Excluding the coarse fragments, the remaining material was approximately 82-86% sand, 10% silt, and 4-8% clay. The mix of both fine fractions and coarse gravel content provided a balance of suitable vegetation growth media and erosion resistance. Drill seeding using a mixture of grasses (green sprangletop, alkali sacaton, sand dropseed, plains bristlegrass, switchgrass, blue grama, buffalograss, Indian rice grass, bottlebrush squirreltail, Western wheatgrass, purple threeawn, bush muly), forbs (sweetclover, Mexican hat, blue flax), and shrubs (four-wing saltbush, New Mexico forestiera, mountain mahogany) at an application rate of approximately 19 lbs/acre was completed in 2007. The planting of piñon pine and Rocky Mountain juniper tree seedlings was performed in Spring 2008. Comparison photographs of the pre- and post-reclamation condition of Dump 1-A are shown in Figure 7. A qualitative inspection by MMD personnel in Fall 2010 revealed that the reclamation of Dump 1-A appeared successful. Little evidence of erosion was visibly apparent, and the grasses and forbs appeared largely well established. Qualitatively, the tree seedlings and shrubs appeared to be less successful than the grasses and forbs. Future work to be conducted includes a quantitative assessment of overall vegetative growth.

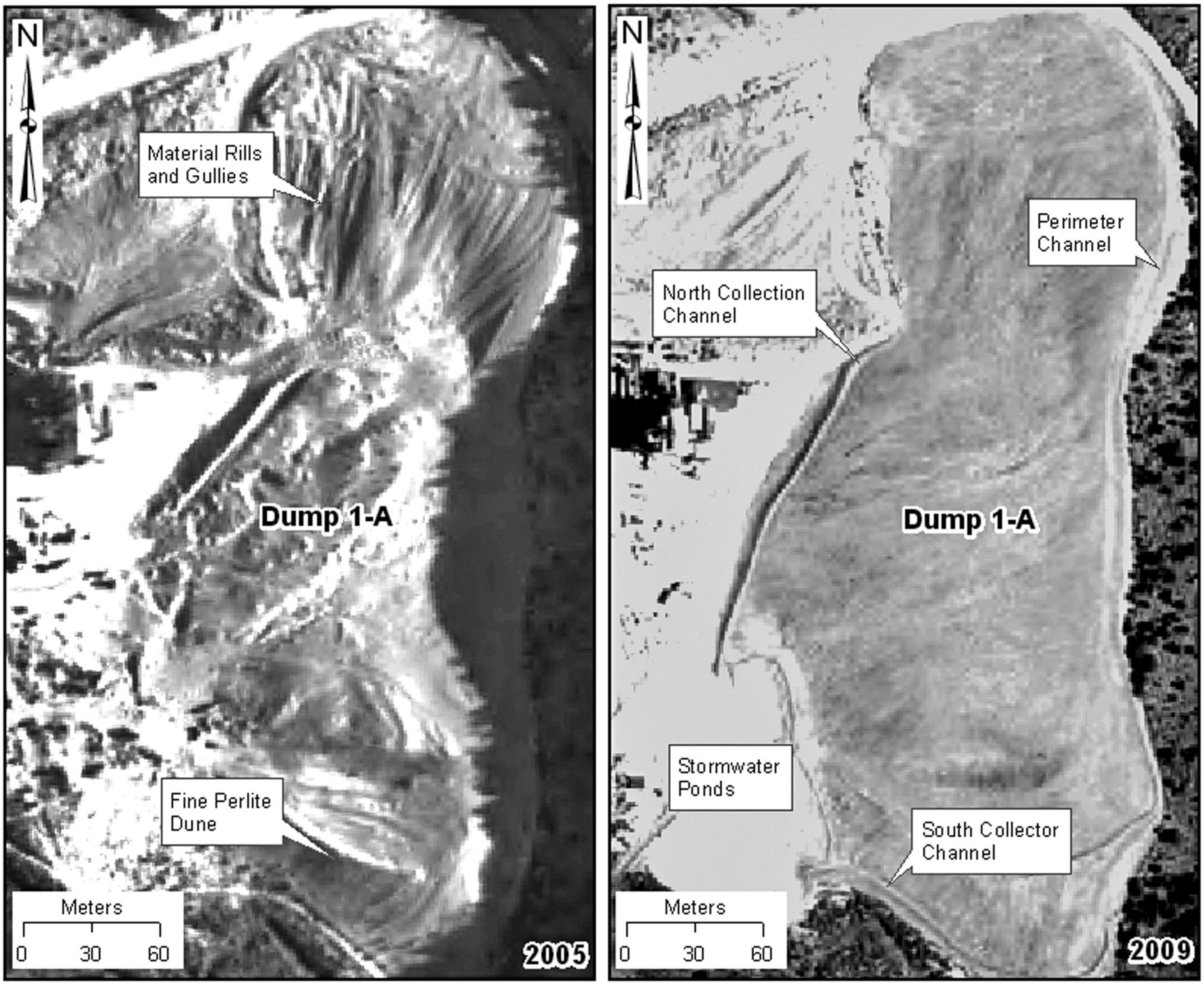

FIGURE 6: Aerial photographs of Dump 1-A showing pre-reclamation condition (2005) and post-reclamation condition (2009). Aerial photograph dated 2005 is from the New Mexico Geospatial Data Acquisition Committee (2006). Aerial photograph dated 2009 is from the National Agriculture Imagery Program (NAIP; 2009).

No Agua Mine

The No Agua Mine, operated by Harborlite Corporation (Harborlite), is an active perlite mine located on the north peak and on the southwest flank of the south peak in the No Agua Peaks. In total, the No Agua Mine consists of approximately 516 permitted acres, and has an estimated 276 acres of mining-related disturbance from a milling plant, various buildings, two open pits, roads, various waste rock dumps, and an elongate perlite fines (mill reject) dump. In preparation for reclamation at the conclusion of mining, Harborlite has initiated a test plot program to test various waste materials for potential future use as a vegetative growth media, as well as develop successful reclamation techniques.

Harborlite's re-vegetation program consists of three on-going test plot areas (Fig. 8) and four reference areas, which are areas that are unaffected by mining and provide a baseline condition from which re-vegetative success can be measured. The percent coverage of the four reference areas was found to range from 34.5% (on the top of the south peak of No Agua Peaks) to 99% (in gentler topography south of the south peak). Re-vegetative success is being monitored using various techniques such as determination of a statistically adequate sampling size, measurement of vegetative cover using the line interception method, measurement of shrub density using the plot or belt transect method, development of a similarity/diversity index, and determination of vegetation productivity. Each of the test plot areas at the No Agua Mine was planted with a seed mix that is broadly appropriate for

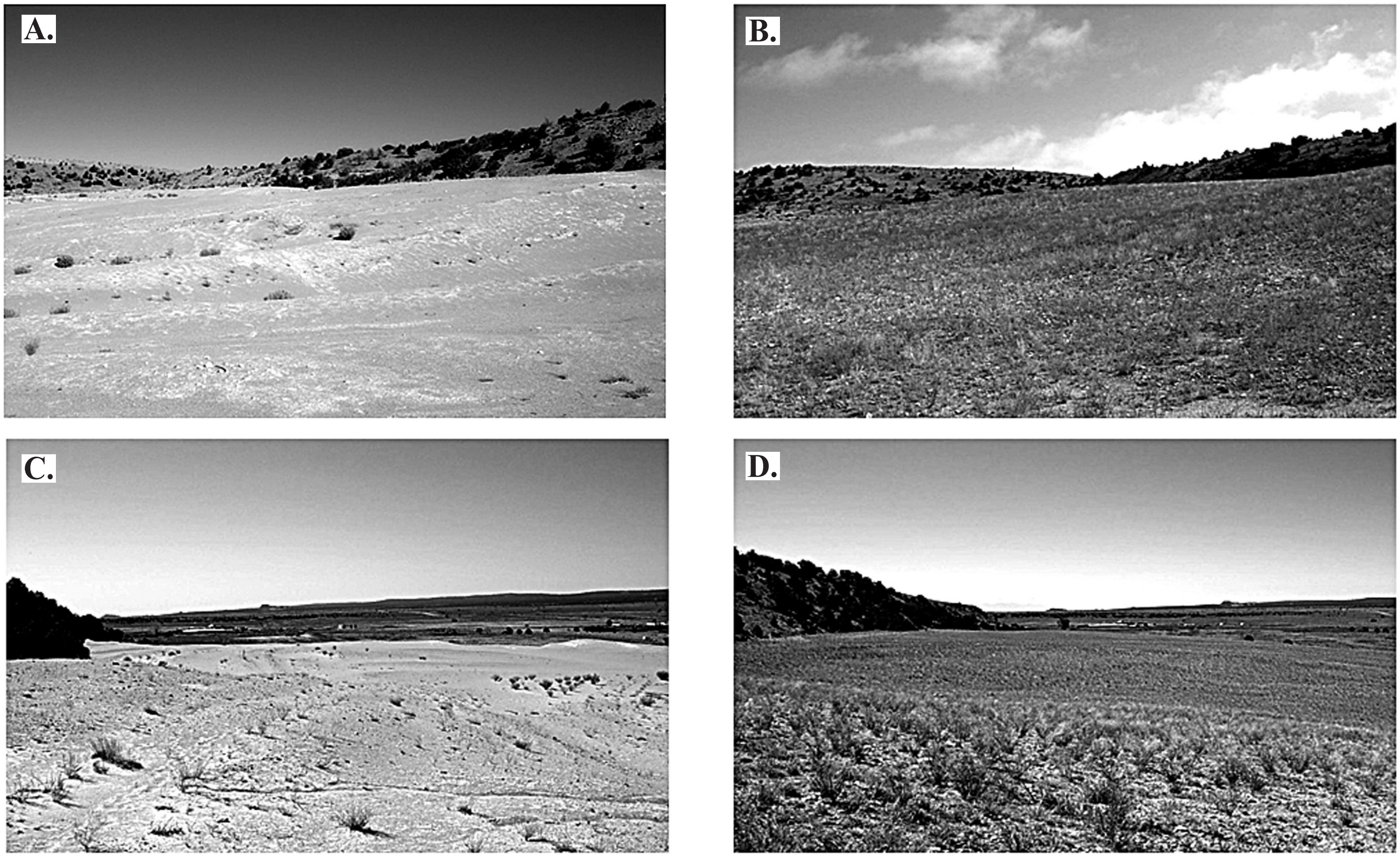

FIGURE 7: Selected views of the Dicaperl El Grande Mine Dump 1-A (fine perlite mill reject material) before and after reclamation. **A.** Looking approximately northeast before reclamation. **B.** Same view as A, after reclamation. **C.** Before reclamation, looking approximately south. **D.** Same veiw as in C, after reclamation. Photos by David Ohori, EMNRD MMD.

regional reclamation for the area. In addition, native tree species were added to the test plots to more accurately represent the typical mix of indigenous flora. Beyond initial planting, no watering, care, or fertilization was applied to the test plots. Ultimately, the target for successful re-vegetation is to find no significant differences between the test plots and the reference areas at a 90% statistical confidence level. For each of the three test plot areas, broadcast seeding was performed in September 2001 at an application rate of approximately 10.3 lbs/acre.

Test plot area 1 is approximately 1.82 acres and is located west of the current fines (mill reject) dump site. This area has mine waste material already in place (silicic and intermediate volcanic rock overburden) as the experimental soil media and is indicative of the type of material that Harborlite intends to use as cover material over the fines dump during final reclamation. In 2009, the total coverage for test plot area 1 was measured at 16.62%, with at least 15 different species present. Rubber rabbitbrush, hairy false goldenaster, and threadleaf ragwort dominated the percent coverage. Rabbitbrush was intentionally seeded in this test plot, while hairy false goldenaster and threadleaf ragwort appear to be volunteer growth. Test plot area 2 is approximately 1.39 ac and is an abandoned road that was chosen to be representative of the roads, mine pads, and pit bottoms that will be present upon cessation of mining. No overburden was placed on this test plot; it is in-situ material with the top surface removed. The total vegetative cover for test plot area 2 in 2009 was measured at 24.86% with at least 14 different species present. Hairy false goldenaster, various unspecified grasses, rubber rabbitbrush, nodding buckwheat, biennial wormwood and Indian rice grass dominated the coverage. Test plot area 3 is 1.58 ac, and is located on an existing mine waste dump. This area was chosen to be representative of the reclamation of overburden mine waste. Total vegetative cover in 2009 was measured at 14.12% with at least 14 species present. Rubber rabbitbrush, various unspecified grasses, and yellow sweet clover were the largest contributors to the cover.

Overall, the three test plot areas have had approximately seven growing seasons from 2001 to 2009, and, qualitatively, show relatively poor coverage for the amount of time allotted. Test plot area 2 appears to be the most successful, likely due to the higher quality of the soil (in-situ soil with the top surface removed), while test plot areas 1 and 3 show relatively low vegetative growth on the overburden mine waste. The re-vegetation test plot study is anticipated to continue through 2013, at which time the final test plot results at the No Agua Mine will be quan-

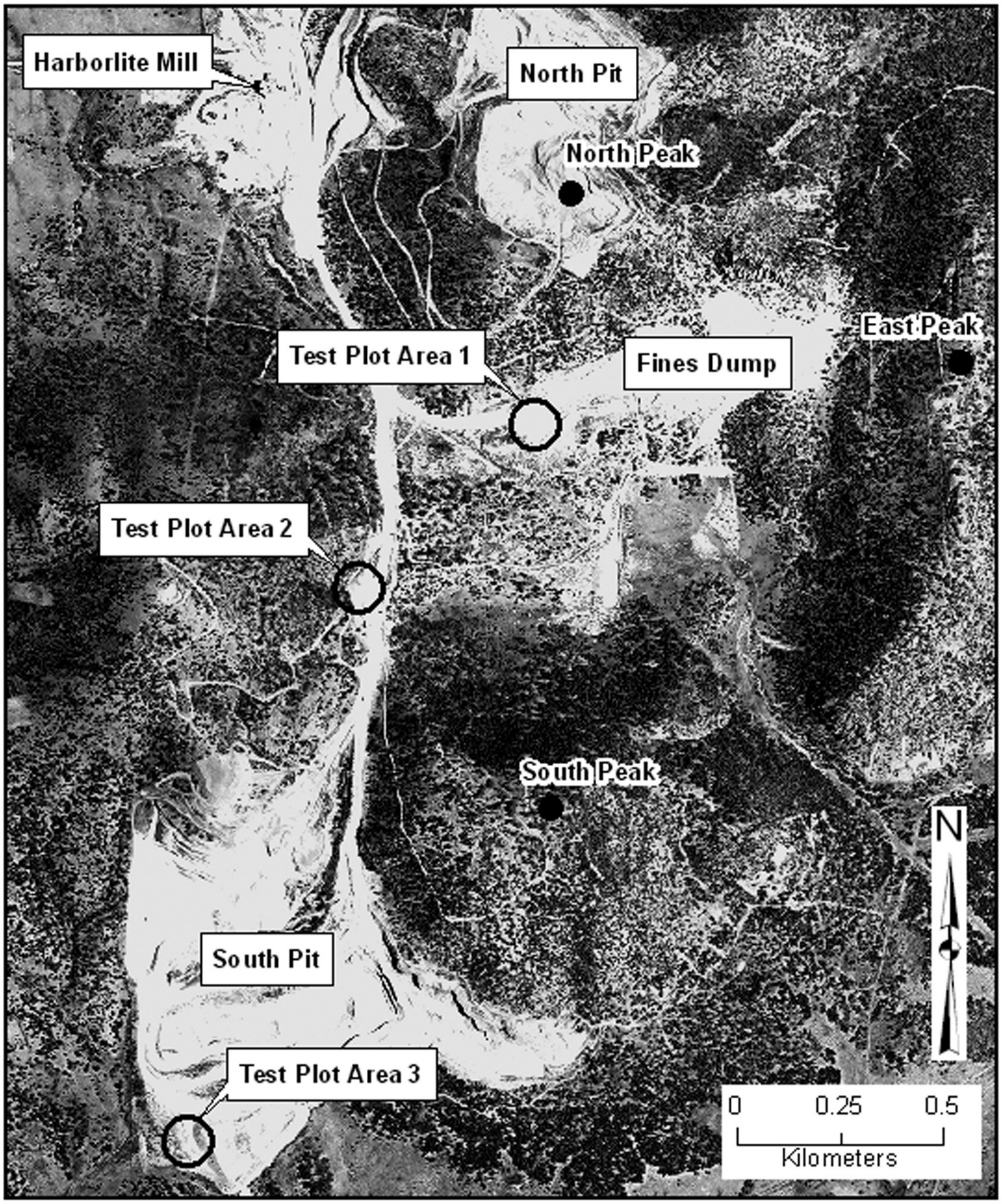

FIGURE 8: Layout of the No Agua Mine showing the locations of the test plot areas. Aerial photograph from National Agriculture Imagery Program (NAIP; 2009).

titatively evaluated in preparation for a final revegetation plan to be implemented upon final closure of the mine. Quantitative assessment of the vegetation within the reference areas will also be completed in the future so that a direct comparison of vegetative success within the test plots may be made.

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