# Galápagos Flora: Fernandina (Narborough) Caldera before Recent Volcanic Event

Abstract. *A collection of 25 flowering plants was made from the inner cone of Fernandina crater. The distribution, relationships and dispersal mechanisms of these species are considered in the light of recent physical changes resulting from volcanic activity.*

The biota of the large Galápagos island of Fernandina (Narborough) is still virgin, having been protected from human interference by the barren outer slopes of inhospitable lava flows. The island is the summit of a submarine volcano rising about 1320 m above the sea and containing a caldera 4 km across and about 550 m deep. A shrubby forest, dominated by *Scalesia* trees, occupies the summit, covering the flat ring between the edge of the caldera and the outer slope. This forest vegetation has not been described other than in popular accounts.

Until June this year, parts of the inside walls of the caldera were also forested and there was vegetation on a secondary tufa cone which rose from the cooled lava lake of the caldera floor (*1*). In June there was a major volcanic event on Fernandina, involving an explosion in the multimegaton range and further collapse of the caldera (*2*). Fortunately, one of us had collected plants from the inner cone in 1966.

The 25 species represented in the collection are listed in Table 1. Of those with complete identifications, all are native to the Galápagos Islands and over a third are endemic. All have been found on the neighboring island of Isabela (Albemarle). Six are new records for Fernandina, but this may be taken to be a reflection of the lack of work on the island.

Table 1. Distribution of the plants collected from the central cone of Fernandina. Where no data were available, a question mark is used. Species not previously known from Fernandina's outer crater (as shown by a minus sign in that column) are new records for the island. Past collections were limited to the outer slopes of the mountain; this is the first account of the flora of the crater floor. Species of Compositae and Asclepiadaceae were probably wind-dispersed; all other species were probably bird-dispersed.

| Species (*7*) | Family | Galápagos distribution (*8*) | | | |
|---|---|---|---|---|---|
| | | Fernandina (outer crater) | Isabela | Other islands | Endemic to Galápagos |
| *Alternanthera* sp. | Amaranthaceae | ? | ? | ? | ? |
| *Sarcostemma angustissima* (Anderss.) Holm | Asclepiadaceae | + | + | + | + |
| *Tournefortia pubescens* Hook. f. | Boraginaceae | + | + | + | + |
| *Bursera graveolens* (HBK) Tr. & Pl. | Burseraceae | + | + | + | — |
| *Drymaria cordata* (L.) Willd. | Caryophyllaceae | — | + | + | — |
| *Baccharis pingraea* DC. var. *angustissima* DC. | Compositae | + | + | + | — |
| *Darwiniothamnus lancifolius* (Hook.) Harl. ssp. *glandulosus* (*9*) | Compositae | + | + | — | + |
| *Pectis tenuifolia* (DC.) Sch. Bip. | Compositae | + | + | + | — |
| *Cyperus anderssonii* Böckeler | Cyperaceae | + | + | + | + |
| *C. ligularis* L. | Cyperaceae | — | + | + | — |
| *Acalypha* sp. | Euphorbiaceae | ? | ? | ? | ? |
| *Euphorbia* sp. | Euphorbiaceae | ? | ? | ? | ? |
| *Aristida subspicata* Tr. & Rupr. | Gramineae | + | + | + | — |
| *Cenchrus platyacanthus* Anderss. | Gramineae | + | + | + | + |
| *Setaria setosa* (Sw.) Beauv. | Gramineae | + | + | + | — |
| *Trichoneura lindleyana* Eckm. var. *lindleyana* | Gramineae | + | + | + | — |
| *Cassia occidentalis* L. | Leguminosae | — | + | + | — |
| *C. picta* G. Don | Leguminosae | + | + | + | — |
| *Crotolaria pumila* Orteg. | Leguminosae | + | + | + | — |
| *Phaseolus mollis* Hook. f. | Leguminosae | — | + | + | + |
| *Rhynchosia minima* (L.) DC. | Leguminosae | + | + | + | — |
| *Stylosanthes sympodialis* Taub. | Leguminosae | — | + | + | — |
| *Borreria suberecta* Hook. f. | Rubiaceae | — | + | + | + |
| *Waltheria reticulata* Hook f. | Sterculiaceae | + | + | + | + |
| *Lippia rosmarinifolia* Anderss. | Verbenaceae | + | + | + | + |

To reach the central cone of Fernandina from the nearest parent stock on Isabela, the seeds or propagules have had to cross some 10 or more kilometers of sea and a further 10 km of waterless lava. It is not surprising to find that all the plants belong to families known to be dispersed by wind or birds (*3*). Dispersal of seeds carried in the digestive tracts of birds (*4*), on their feathers, or in mud on their feet (*3*) over such distances is obviously possible.

The tufa cone, surrounded as it was by unweathered, cooled lava, was evidently a geologically young feature, so that the flora may profitably be compared with the first colonists of Krakatoa following the famous eruption. Although Krakatoa was in a much more favorable climate for plants and was close to richly vegetated islands on the other side of the world, no less than ten of the Fernandina families and four genera are listed among the early colonists of Krakatoa (*5*).

One of us (P.A.C.) reached the rim of the Fernandina caldera on 10 July 1968, following the volcanic event, and photographed the tufa cone. Continuous avalanches down the crater walls prevented closer inspection of the cone, but the general appearance of its surface and the magnitude of the explosion suggest that the plants may have been mostly killed or buried. However, the *Scalesia* forest of the summit, together with its animals, was almost unaffected.

The floor of the crater, including the cone, seems to have fallen several hundred meters from its old elevation of about 770 m above sea level, perhaps changing the environment of the cone. Study of the recolonization process should prove rewarding. The plant collection of 1966 may serve as an interesting basis for comparison. Although the caldera is thought to be somewhat inaccessible, recent experience shows that work there is quite practicable (*6*).

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### References and Notes

1. P. A. Colinvaux, *Nature* **219**, 590 (1968).
2. Smithsonian Institution, Center for Short Lived Phenomena, Event Notification Report, Galápagos Volcanic Eruptions, June 1968.
3. S. Carlquist, *Bull. Torrey Bot. Club* **94**, 129 (1967); H. B. Guppy, *Observations of a Naturalist in the Pacific between 1896 and 1899*, vol. 2, *Plant-Dispersal* (Macmillan, London, 1906), p. 627.
4. V. W. Proctor, *Science* **160**, 321 (1968).
5. A. Ernst, *The Flora of the Volcanic Island of Krakatau* (Cambridge Univ. Press, Cambridge, 1908), p. 38.
6. R. Perry, director of the Charles Darwin Station, has made descents into the crater. The climb involved is described in P. A. Colinvaux, report 2161-1, Research Foundation, Ohio State University (1967) and P. A. Colinvaux, *Animals* **11**, 297 (1968). Popular accounts of the severity of the Galápagos conditions are not to be believed.
7. Wiggins identified all plant specimens, except the Cyperaceae which were named by T. Koyama, New York Botanical Garden, and the Gramineae, identified by J. R. Reeder, University of Wyoming. Species names were not available for three specimens, which are still being studied by specialists.
8. A. Stewart, *Proc. Calif. Acad. Sci. Ser. 4* **1**, 7 (1911).
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10. Contribution No. 102 from the Charles Darwin Foundation for the Galápagos Isles. The work of P. A. Colinvaux and E. K. Schofield is supported by NSF grants GB-4654 and GB-7154.

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## Chemical Potential of Water from Measurements of Optic Axial Angle of Zeolites

*Abstract.* *Values of the uncorrected optic axial angle* ($2H_\alpha$) *of a crystal of the calcium zeolite stellerite* ($CaAl_2Si_7O_{18} \cdot 7H_2O$) *immersed in calcium chloride solutions of known activity of water* ($a_w$) *are directly proportional to log* $a_w$. *A general relationship between the chemical potential of water in the crystal and the optic axial angle is obeyed.*

Some of the water in zeolite crystals is loosely bound and can be transferred in and out of the crystal. Structural changes brought about by variation in the water content of zeolites are reflected in changes in the optical properties of the crystal. We here report that for the orthorhombic calcium zeolite stellerite ($CaAl_2Si_7O_{18} \cdot 7H_2O$), the uncorrected optic axial angle ($2H_\alpha$) (*1*) is related to the chemical potential of water in the crystal $\mu_w$ by the general equation:

$$\mu_w - \mu_w{}^0 = 2.303RTS^{-1} \times [(2H_\alpha) - (2H_\alpha)^0] \quad (1)$$

where $R$ is the gas constant; $T$ is the absolute temperature; $S$ is a numerical constant for the system which consists of crystal plus solution having chemical potential of water; $\mu_w$; $\mu_w{}^0$ and $(2H_\alpha)^0$ are standard-state values at an activity of water ($a_w$) equal to unity. The specific equation for a stellerite crystal immersed in $CaCl_2$ solutions of varying $a_w$ at 25°C is:

$$\mu_w - \mu_w{}^0 = -0.167\,[(2H_\alpha) - 35.4] \quad (2)$$

where $\mu_w$ is in kilocalories per mole and $(2H_\alpha)$ is in degrees.

A small crystal of stellerite (0.25 by 0.25 by 0.6 mm) was selected from a purified sample collected at a new occurrence near Chena Hot Springs, Alaska. The chemical analysis of the sample from which the crystal was selected indicates a composition near the theoretical one (*2*), with 0.07 percent sodium (by weight) and no potassium (*3*). Principle indices of refraction at 25°C for sodium light were determined with immersion liquids of known refractive index and a spindle stage; indices of refraction for $(2V_\alpha)$ were determined with a four-axis Fedorow stage; the results are $N_\alpha = 1.486 \pm 0.002$, $N_\beta = 1.494 \pm 0.002$, and $N_\gamma = 1.498 \pm 0.002$; $(2V_\alpha) = 45.0° \pm 0.2°$ (average deviation). The crystal was then mounted on a glass fiber and placed in a Waldmann hollow-glass sphere. The sphere was successively filled with eight different $CaCl_2$ solutions; the crystal was equilibrated with $CaCl_2$ solution at 25° ± 0.1°C for a minimum of 24 hours, after which $(2H_\alpha)$ was measured. The solutions ranged from 0.460 to 7.89 molal, corresponding to a range in $a_w$ of 0.978 to 0.259.

The $CaCl_2$ solutions were prepared by dissolving $CaCl_2 \cdot 2H_2O$ (Mallinckrodt analytical reagent grade) in de-ionized water. This reagent contains 0.169 percent maximum impurities, with insignificant amounts of cations that might exchange with the calcium of the stellerite. The molality of each solution was determined by measuring the density of the solution and converting it to concentration (*4*). Values of $a_w$, as a function of molality, were obtained from Robinson and Stokes (*5*).

Measurement of $(2H_\alpha)$ of the crystal during immersion in each solution was accomplished by orienting the Waldmann sphere on the universal stage in such a way that the position of both melatopes could be reached by rotation about $A_4$ (outer east-west axis) with minimum and approximately equal angles of tilt. In each case three sets of readings were obtained; these were checked by three additional sets of measurements with the optic axial plane rotated 180° by appropriate adjustments of $A_1$ (inner vertical axis) and $A_2$ (north-south axis). The six values of $(2H_\alpha)$ observed were averaged, and the average deviation was calculated. For the eight $CaCl_2$ solutions and pure water, the largest difference (Table 1) between maximum $(2H_\alpha)$ and minimum $(2H_\alpha)$ for a given solution is 1.8°; the average difference is 1.1°. The average of the six readings made for each solution is somewhat more precise, as indicated by the values of the average deviations. The molality of $CaCl_2$ and $a_w$ are known precisely enough so that these values contribute no error to the measurements.

The transfer of water into and out of the stellerite is reversible; within experimental error, the same value of $(2H_\alpha)$ is found for a solution of given $a_w$ before and after the crystal is immersed in a solution of different $a_w$.

Table 1. Measured apparent optic axial angles $(2H_\alpha)$ at 25°C of a stellerite crystal immersed in $CaCl_2$ solutions. Average values for $(2H_\alpha)$ are based on six measurements.

| Molality | $a_w$ (25°C) | $(2H_\alpha)$ (degrees) Maximum | Minimum | Average | Av. dev. |
|---|---|---|---|---|---|
| 0 | 1 | 36.2 | 35.0 | 35.4 | 0.5 |
| 0.460 | 0.978 | 35.8 | 35.1 | 35.4 | .3 |
| $1.97_8$ | .864 | 36.1 | 35.7 | 35.9 | .1 |
| $3.28_2$ | .714 | 37.2 | 36.1 | 36.6 | .4 |
| $4.13_9$ | .588 | 37.6 | 36.5 | 37.2 | .3 |
| $5.03_3$ | .496 | 38.6 | 37.2 | 37.9 | .4 |
| 6.25 | .369 | 39.5 | 38.3 | 38.8 | .4 |
| 7.37 | .289 | 41.0 | 39.2 | 39.8 | .6 |
| 7.89 | .259 | 40.8 | 39.9 | 40.2 | .3 |