The mineralogical microstructure of shells: PART 2. The iridescence colors of abalone shells

M.R. SNOW* AND A. PRING

South Australian Museum, North Terrace, Adelaide, South Australia 5000, Australia

ABSTRACT

The iridescence colors of abalone shell arise from Bragg diffraction of light from the layers of the nacre. The thickness of the aragonite nacre tiles is locally regular but varies during the growth cycles of the shell and this can give rise to complex color play. In Paua shell (Haliotis iris) and in H. fulgens (particularly the muscle scar shell) the thickness of the nacre tiles varies from 0.25(3) to 0.39(3) μm, but locally the thickness is constant within domains of hundreds of tiles. Other species such as H. laevigata and H. rufescens are similar, but their tile thicknesses range from 0.35(4) to 0.52(4) μm. In all species, the color displayed changes with observation angle and is due to layer diffraction. In H. iris and H. fulgens, the colors displayed encompass the complete visible spectrum; color hues are pure and are well-defined first-order diffraction colors. Shells of the other species display red and green, but not blue colors. The colors are rendered most vividly where dark organic growth layers are formed. These absorb or scatter light and enhance the iridescence colors. The origin and nature of the diffraction colors are compared with those observed in labradorite and opal. The degree of regularity in tile thickness needed to allow diffraction colors to be generated is modeled using pearl (sheet nacre) and abalone shell (columnar nacre) as examples. The wavelength dispersion is proportional to the product of the squares of the refractive indices of the material, the normalized standard deviation of the thickness, and the order of the diffraction color. For this reason, only first-order diffraction color is seen from shells.

INTRODUCTION

This research is directed toward understanding the origin of structural color in shells and pearls. This phenomenon has been widely investigated in other animal systems (Parker 1998) and minerals (Nassau 1978). Some early attention has been given to shell structure and color (Brewster 1814; Raman 1934; Ball 1982) and recent work has been concerned with surface effects (Liu et al. 1999; Liu 2001; Tan et al. 2004). There are many mechanisms behind the origin of color in minerals, and these were discussed comprehensively by Nassau (1978). In only a very few cases in minerals, does color arise by diffraction from repeating structural features. The color play in both precious opal (Saunders 1964, 1968; Darragh and Saunders 1971) and feldspars with intergrown phases, such as labradorite (Bolton et al. 1966) and moonstone, are understood in this way. For opal, which consists of closed-packed arrays of uniform-sized silica spheres, the longest wavelength observed is related to the radius, \( r \), of the silica spheres by \( \lambda_{\text{max}} = 5.02r \) (in μm). For example, to produce red colors, \( r \) needs to be about 0.15 μm, and such opals will also display not only red but also the full spectrum of colors. Where \( r \) is small, near 0.08 μm, only violet color will be seen. For labradorite, the color (called schiller) arises from diffraction by intergrowths of exsolution lamellae having different compositions and refractive indices. The thicknesses of the exsolution lamellae are in the range of 0.6 to 1.7 μm. The wavelength of reflection maximum in labradorite is predicted from Bragg’s law with about 10% accuracy from the thicknesses of the lamellae pairs due to variation in the material. For instance, for normal incidence of light onto lamellae pair thicknesses of 1.4 μm, only blue color is seen, i.e., “blue labradorite.” The wavelength of maximum intensity shifts to the UV at lower angles of incidence. Thus only blue iridescence is ever seen in this material. For red labradorite, however, a range of colors is possible at different viewing angles.

In addition to diffraction, which occurs in geometrically well-ordered materials, light scattering can occur from partly ordered material. This produces whitish and bluish colors. The latter has been given various names, including adularescence, aventurescence, and opalescence, leading to a confused terminology (Nassau 1978). The term adularescence is used for the feldspar colloquially called moonstone, in which the color can range from the full rainbow to a single color, usually blue. Bolton et al. (1966) concluded that the difference between the origin of color in the feldspars labradorite and moonstone lay in the lower degree of regularity in the thickness of the alternating lamellar phases of moonstone. All these materials and abalone shell are of gemological interest. They have been discussed by Webster and Anderson (1983), but a proper quantification of the color from the biomineralized materials has not been offered.

The Scottish physicist Sir David Brewster (1781–1868) investigated the optics of mother of pearl. Brewster (1814) divided...