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A long-term increase in eggshell thickness of Greenlandic Peregrine Falcons *Falco peregrinus tundrius*

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Abstract

Thickness of eggshell fragments and whole eggs from the Peregrine Falcon *Falco peregrinus* collected in South and West Greenland between 1972 and 2003 was measured and compared to shell thickness of pre-DDT eggs, also collected in Greenland. Linear regression yields a significant increase in the average thickness of eggshells over the period of 0.19% per year, corresponding to a change in eggshell thinning from 13.9% in 1972 to 7.8% in 2003. Backwards extrapolation of the data, suggests that the Greenlandic Peregrine population probably was never critically affected by DDT-induced eggshell thinning. By sampling eggshell fragments in many nests the spatial and temporal sample distribution was enlarged, allowing the detection of a significant long-term decrease in pollutant-induced eggshell thinning—a trend that could not have been identified if only the rarer whole, addled eggs had been sampled.

Keywords: Peregrine Falcon; *Falco peregrinus*; Eggshell thickness; Greenland; Arctic

1. Introduction

The effects of persistent organic pollutants (POP) on the eggshell thickness and breeding success in high-trophic level birds have been widely documented. Especially DDT and its derivatives have been identified as a key group of POPs responsible for the widespread reduction in breeding success and subsequent population decline in the Peregrine Falcon *Falco peregrinus* (Hickey, 1969; Hickey and Anderson, 1968; Newton, 1979; Peakall et al., 1975, 1976; Peakall and Kiff, 1979; Peakall and Lincer, 1996; Ratcliffe, 1970, 1993; Walker II et al., 1973).

The Greenland Peregrine Falcon (*F.p. tundrius*) population has been the subject of long-term studies in West Greenland since 1972 (e.g. Burnham and

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Mattox, 1984; Mattox and Seegar, 1988; Restani and Mattox, 2000) and South Greenland since 1981 (Falk et al., 1986; Falk and Møller, 1988). The Greenland population was conservatively estimated at 500–1000 pairs (Falk and Møller, 1988). Autumn migration counts in the eastern US, where Peregrines from Greenland and the eastern Canada mix during the migration, suggest a slight increase in Arctic populations (Titus and Fuller, 1990). It is thus to be expected that a population of Arctic Peregrines possibly recovering from the effects of POP-exposure will show an increase in eggshell thickness over time.

Eggshell thickness analyses have often relied on measurements of whole dead eggs, which, however, i) are relatively rare occurrences, ii) are not present in the most successful nests (all eggs hatch), and iii) may potentially be biased since very thin eggs might break (Odsjö, 1982). By using eggshell fragments from all nests, a more representative and comprehensive survey of the wild population can be obtained. Based on the intra- and inter-clutch variation in shell thickness, Falk and Møller (1990) recommended that studies of eggshell thinning should include fragments from as many nests as possible.

Although studies of Arctic Peregrine Falcon populations have shown that thinning in recent eggs is less severe than older samples (Ambrose et al., 2000; Johnstone et al., 1996), no gradual time trends have been documented, probably due to relatively short duration of most field studies. This paper presents the results of a 32-year study of changes in eggshell thickness in Greenlandic Peregrines, in order to test the assumption that shell-thinning is continuously improving following the general reduction in use of the contaminants causing the effect.

2. Materials and methods

2.1. Study area and sampling

The study combines samples from two study areas (Fig. 1): South Greenland (samples from 1981–2003), and West Greenland (samples from 1972–1988).

The South Greenland study area covers the inner parts of the three southernmost municipalities of Southwest Greenland, Nanortalik, Qaqortoq and Narsaq, approx. within 60°–61° N and 45°–46° W. The area is low Arctic, with tundra vegetation, and willow and birch shrub in the warm, sub-arctic areas far from the cool outer coast. A substantial part of the area is grazed by sheep. Field surveys of the Peregrine Falcon population have been conducted here annually between 1981 and 2003 by KF and SM.

The West Greenland study area covers the low-arctic inland areas around Kangerlussuaq (Søndre Strømfjord), approx. within 66° 45′–67° 15′ N and 50°–52° W. The area is hilly/mountainous and dotted with lakes, and is divided by the large fjord Søndre Strømfjord. The main vegetation is treeless tundra (Burnham and Mattox, 1984). Studies were initiated in 1972 by WGM and Richard Graham (see Burnham and Mattox, 1984), and the present paper includes eggshell fragments from 1972–1988.

In both survey areas, active nests were visited at least once post-hatching, and, when conditions allowed, the nest scrape carefully searched for eggshell fragments deriving from the hatched eggs. In addition, any whole dead eggs present were collected for contaminant analyses; whole eggs are included in this paper for comparison with fragments, while contaminant studies of the egg contents from South Greenland will be published elsewhere.

2.2. Measurements and analyses

The shell fragments were measured with a computer-connected Mitutoyo Digital Micrometer (type 293-521-30) with a small stainless steel ball glued to the rotating jaw in order to fit the inner curved surface of the eggshell fragments.

Each fragment was scrutinised to determine whether any membrane was still adhering to the inner surface. Measurements were performed only on (parts of) fragments without any membrane because on fragments it is difficult to be certain if both membranes (shell and egg membrane) are present.

Samples from a total of 93 clutches from South Greenland were measured and provided from 3 to 91 membrane-free measurements. However, since eggshell thickness varies within the egg there is a risk that too few samples may bias results. Hence, we chose to include only 79 clutches that provided 20 or more measurable fragments—the same threshold selected by Odsjö (1982) in a study of Swedish Ospreys—and assumed they represented the thickness of the entire

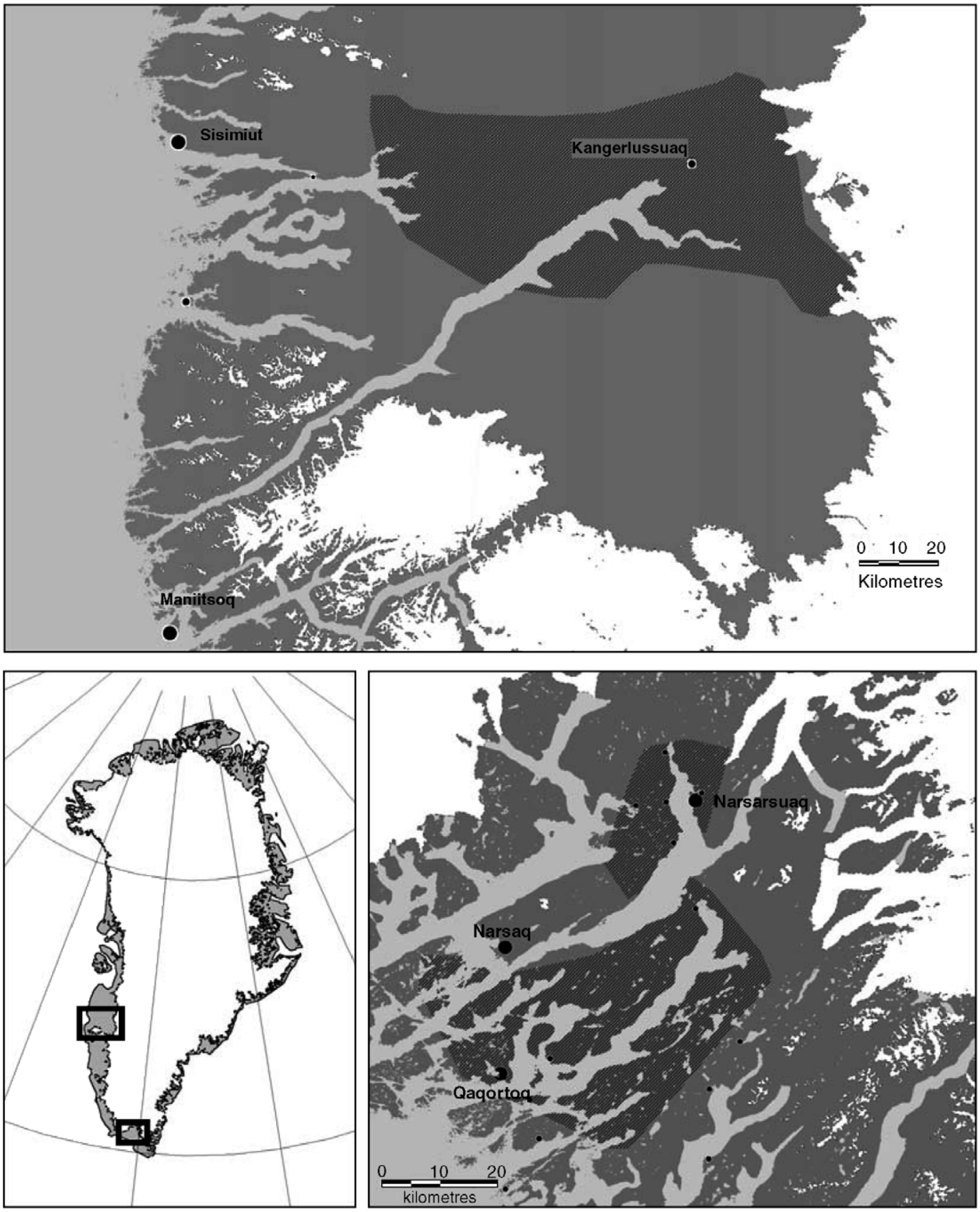

Fig. 1. Sampling sites in South and West Greenland; all nest sites sampled in this study are located inside the hatched areas. White inland areas are ice/glaciers.

clutch. Similarly, among 58 samples from West Greenland, 40 clutches provided at least 20 measurable fragments.

Whole, addled eggs were also collected and kept frozen, and used for eggshell measurements: in South Greenland 38 eggs from 28 clutches (1986–2003), and in West Greenland 8 eggs from 8 clutches (1986–88). When opened in the laboratory for contaminant studies (Sørensen et al., 2004), the eggs were cut along the equator and the empty half shells washed with water before being left to dry for 3 months at room temperature. The half shells were measured along the equator with a modified Mitutoyo Micrometer (type 147-301)—the same device used to measure 16 Greenlandic pre-DDT clutches (48 eggs) in the collection at Zoological Museum, Copenhagen (Falk and Møller, 1990). There was no significant difference in measurements taken with the two different tools. The egg opening method left parts of the shell with membranes intact and other parts without membranes. Consequently, most measurements include membranes, but some are without. To compare measurements with and without membranes, a membrane correction factor was independently determined by measuring adjacent points with and without membranes on 26 whole eggs (the cut halves): 0.071 mm (n=83, SD=0.013). This compares well to the 0.07 mm used by Nygård (1983) and 0.069 mm reported by Court et al. (1990).

The sampling unit used in all analyses is 'clutch'—i.e., each nest and year provides one mean eggshell thickness value.

3. Results

Mean shell thickness for fragments from South Greenland and West Greenland did not differ when comparing data from 1981–1989, the period during which samples from both areas were available (t-test;

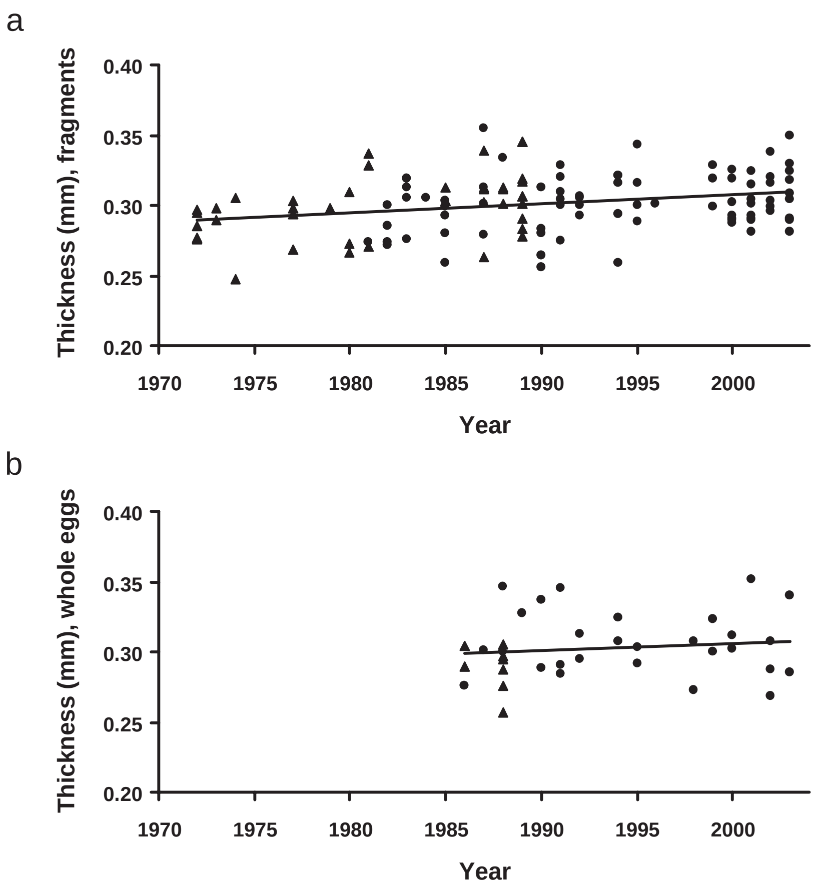

Fig. 2. Eggshell thickness vs. sampling year of Peregrine Falcon eggs from South (circles) and West Greenland (triangles) based on: a) eggshell fragments 1972–2003 (linear regression: y=0.000655 x -1.0018), and b) whole addled eggs 1986–2003 (y=0.000525 x -0.74296, ns).

df=20, 22; P=0.123). Hence, further analyses are based on pooled data samples from the two survey areas.

During the period 1972–2003 there was a weak but highly significant increase in the average thickness of eggshell fragments (Fig. 2a) (P=0.00223, N=119). The slope of the linear regression shows an average increase of 0.19% per year. This would correspond to a change in eggshell thinning from 13.9% in 1972 to 7.8% in 2003 when compared to pre-DDT eggs collected in Greenland (48 eggs from 16 clutches, 1881–1930, mean 0.336 mm, SD=0.026; Falk and Møller 1990). When data from the two sampling areas were treated separately, the increases were still significant (Table 1). An analogous analysis of data from whole egg samples revealed a similar, but insignificant, increase, although the regression slopes (SAS proc glm, separate slopes model) of the fragment and whole egg samples did not differ significantly (P=0.8224).

When the fragment samples were grouped into two equal time periods, the oldest samples were on average significantly thinner than the more recent (1972–1987: 0.294 mm; 1988–2003: 0.304 mm; t-test, df=37, 66; P=0.0064).

Mean shell thickness for whole eggs and fragments did not differ when comparing data from the period (Fig. 2b) where both types of samples were collected (1986–2003; t-test, df=80, 35; P=0.536), so we also pooled data for the two sample types for a combined analysis.

Several females with known identity provided samples for more than one year. However, no trend could be detected in eggshell thickness with age of the laying bird.

4. Discussion

Although the embryo may extract minerals from the eggshell, it has been shown that while shell density (measured as shell index, Ratcliffe, 1967) is affected, the shell thickness per se does not change significantly during incubation (Bennett, 1995; Bunck et al., 1985). Hence, stage of incubation is not considered in this study.

Walker II et al. (1973) compared shell thickness of material from 9 eggs (2 whole eggs and fragments from 7 eggs) collected in West Greenland to 42 pre-DDT eggs from Greenland and measured a 14% thinning. Similarly, in a previous assessment based on our samples from South Greenland 1981–1985 compared to the same collection of Greenlandic pre-DDT eggs, we arrived at 14% eggshell thinning (Falk and Møller, 1988). Based on the regression equation from this study, the shell thinning in 1983 was 12%, which is in reasonably good agreement with the previous results.

In an early review Peakall and Kiff (1988) reported post-DDT eggshell thinning in Peregrine populations from 30 different study areas across the world ranging from below 5% and up to 25%. Among these, northern migrating populations had eggshell thinning values between 13% and 23% in the 1960s and 70s (Berger et al., 1970; Burnham and Mattox, 1984; Cade et al., 1971; Nelson and Myres, 1975; Nygård, 1983; Odsjö and Lindberg, 1977; Peakall et al., 1975; White and Cade, 1977). More recent studies of eggshell thinning in Arctic migrating Peregrine populations show values of 10.6% (Alaska, 1991–95, Ambrose et al., 2000) and 15% (Arctic Canada, 1990–1994, Johnstone et al., 1996). No time trend

Table 1
Results of linear regression analysis of thickness data of eggshell fragments and whole Peregrine Falcon eggs sampled in South and West Greenland; sample size, N, is number of clutches

Sample	Years	% increase per year*	N	P**	% reduction in 1950***
Fragments, pooled	1972–2003	0.19	119	**0.0022**	18.1
Fragments, South Greenland	1981–2003	0.21	79	**0.0253**	19.4
Fragments, West Greenland	1972–1989	0.44	40	**0.0063**	24.9
Whole eggs, pooled	1986–2003	0.16	34	0.4368	16.6

* Based on linear regression.
** Significance level of the slope; statistically significant values in bold.
*** Extrapolation, based on linear regression.

could be detected in any of these studies, probably due to the relatively short time span covered.

We have found a highly significant long-term gradual increase in the shell thickness over the 32 year survey period, supported by the grouped comparison of equal time periods. If we assume the trend to be linear, the regression line can be extrapolated backwards (Table 1, Fig. 3) for a rough assessment of when the shell-thinning would have exceeded the critical empirical “threshold” of about 17% (Peakall and Kiff, 1988). This rough assessment suggests that the shell-thinning might have exceeded the critical limit until in the early 1950s only. That was probably too short after DDT became widespread (introduced 1947) for the pesticide to have had a marked effect on the Greenlandic Peregrine Falcon population. This is supported by evidence of a strong population since the 1970s (Burnham and Mattox, 1984), despite the fact that the Arctic subspecies in Greenland migrates through and/or to areas in Latin America where phasing out of the pesticides has been slower than in North America due to the need to fight Malaria (Raloff, 2000). With the slow rate of increase, it will take several decades before the eggshell thickness in Greenlandic Peregrines can be expected to reach pre-DDT levels.

Compared to other populations, the Greenlandic Peregrines are in a unique position, because they spend the summer on a relatively isolated island colonised by few long-distance migrants, which could carry pollutants with them. The majority of the Peregrines' prey in Greenland consists of resident (Rock Ptarmigan *Lagopus mutus*) or short-distance migrant passerines wintering in the border area of Canada and USA. Only the Northern Wheatear (*Oenanthe oenanthe*) winters in potential DDT-usage areas of West Africa (Lyngs, 2003). Pollutant levels of passerine prey samples in Greenland were low already in the 1970s (Burnham and Mattox, 1984), so the falcons have a clean summer diet.

To our knowledge, this is the first time a significant, gradual increase in eggshell thickness over time has been detected in a Peregrine Falcon population. No improvement in shell thickness between decades (1982–86 vs. 1991–1994) was found in *F.p. tundrius* from Arctic Canada (Johnstone et al., 1996). However, Ambrose et al. (2000) reported that egg thickness increased slightly, though not signifi-

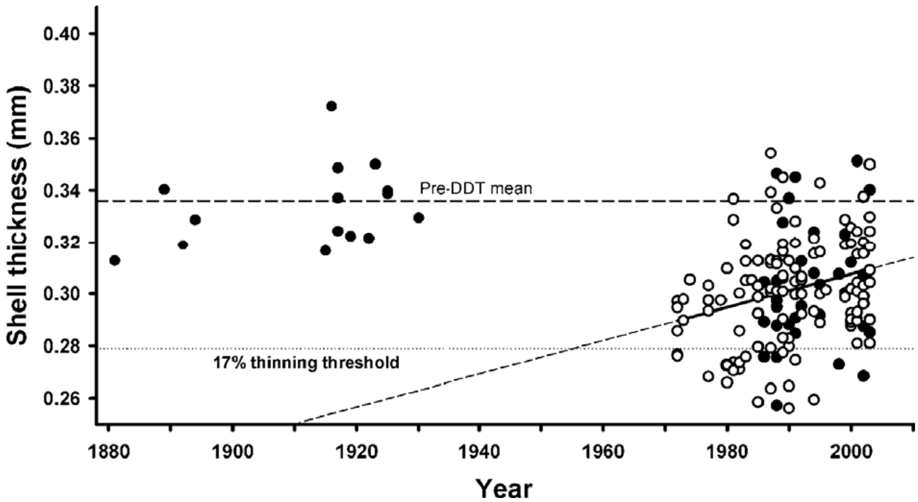

Fig. 3. Shell thickness (mean per clutch and year) of Peregrine Falcon eggs from Greenland; pre-DDT Peregrine eggs (1881–1930) from museum collections, and samples from 1972–2003 from South and West Greenland; filled circles represent whole eggs, and open circles indicate eggshell fragments. The reference lines indicate pre-DDT mean thickness (0.336 mm), and the approximate empiric “17% threshold” (0.279 mm) for population declines (Peakall and Kiff, 1988). The combined regression line of the recent change in thickness is extrapolated backwards.

cantly, over time in Peregrine eggs collected in Alaska 1979-1995.

As a supplement to monitoring the long-term POP loads and effects in Peregrines based on collection of whole addled eggs only (e.g. USFWS 2003) it is worth also to collect and measure the fragments from hatched eggs. In our study it would not have been possible to detect any long-term change in eggshell thickness based on measurements of the whole addled eggs alone; they occur too rarely to provide an adequate sample. By using fragments from hatched eggs—which are easier to obtain and analyse, and probably more representative since they include all breeding attempts—it was possible to expand the temporal and spatial sampling. The larger sampling coverage allowed us to verify that the Greenlandic Peregrine Falcon population is slowly responding to the expected gradually reduced exposure to shell-thinning POPs such as DDT and metabolites.

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