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Purple Dyeing in the Ancient Mediterranean World: Characterisation of Biblical *Tekhelet*

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Abstract

Tekhelet (biblical Hyacinth Purple) was manufactured in antiquity from banded dye-murex (*Phyllonotus trunculus*). It had a violet colour, and chemically its composition is a natural mixture of dyestuffs, blue indigotin and purple 6,6`-dibromoindigotin (DBI).

When the hypobranchial gland contents of male and female banded dye-murex are mixed before all precursors present have formed DBI and indigo-blue, 6-bromoIndIgotIn may be formed. The content of the indigo-blue constituent is thereby lowered. If sufficient MBI is thus produced, the dyeing will not be violet but purple. This explains why banded murex dyeings may vary in hue from reddish to bluish purple.

The author's hypothesis that MBI is chemically unstable, being readily changed into blue indigotin, is experimentally verified. ThIs novel chemical reaction provides the rationalisation for hitherto unexplained anomalies found by many authors who prepared purple dyes from banded murex.

Introduction

The basis for this presentation is the Scripture in Exodus 26:1.

> 'Moreover, thou shalt make the tabernacle with ten curtains, of fine twisted linen and *blue* and *purple* and *scarlet*, with cherubim of cunning work shalt thou make them.'

This trio of colours, 'blue, purple and scarlet', is thus listed together some 30 times in the Bible. They are in the King James` Version of 1611, translating the original Hebrew terms. *Tekhelet* has become 'blue'; *Argaman* 'purple'; and *Tolaat Shani* 'scarlet'. The degree of validity that can be attached today to each of these King James colour assignments is the subject of this paper.

Preliminary considerations

I have spent much of the last 30 years in studying these biblical dyes. In particular I have addressed the questions: How were the colours made? And how were they used?

Argaman ('purple') and *Tolaat Shani* ('scarlet') had already been satisfactorily characterised (Ziderman 19 86a). However, there was no consistent understanding of the *Tekhelet* ('blue'). The production of

Tekhelet had ceased in 7^{th} century Palestine (Herzog 1987). Since then, no authentic remnants were known. The source was forgotten, as was the method of production. Consequently, later writers on the subject could not have employed direct observation for their descriptions and translations but rather relied on previous authorities: thus, the former may not be considered as authoritative and should be disregarded in matters of *realia*.

In the literature, there are conflicting views as to the very colour of *Tekhelet*: Was it really blue, or perhaps purple (Yad in 1963), or turquoise (Feliks 1962, 1981) or violet (Dedekind 1898), or even yellow (in Luther's Bible)?

The aim of my researches has been to characterise *Tekhelet* definitively with regard to colour, provenance, chemistry and preparation.

Correlation with Mesopotamian and Hellenistic sources

Pre-biblical records from Mesopotamia documented that *Tekhelet* was an important treasure in the gentile world too (Herzog 1987). It also merited mention in Mesopotamian literatures contemporaneous with the Biblical era (Herzog 1987). *Tekhelet* was offered in tribute to imperial monarchs by vassal kingdoms. It was extolled as the attire for royalty and heathen idols.

The real key to progress in my understanding of *Tekhelet* came from parallels in the classical world. The Talmud – codification of the Judaic Oral Law – stipulates that:

1. *Tekhelet* is made of wool.
2. It has been dyed with *shellfish*.
3. *Fresh* extract is used.
4. The extract is *clear*.
5. The manufacturing process is detailed.
6. Test dyeing of a sample is described so as to ascertain that the vat is ready.

In the Hellenistic period, there had appeared several Jewish translations of the Bible into *Greek*. They were made when the use of *Tekhelet* in the Second Temple was completely familiar to both the translators and their readers. In these translations, *Tekhelet* was consistently rendered 'hyacinth' (Herzog 1987).

In classical Greek, 'hyacinth' refers to a flower and not to murex purple! However, contemporaneously with these biblical translations into Greek, 'hyacinth' was one of the two main types of purple dyeings described by Roman scholars, in particular detail by the Elder Pliny (Born 1937; Forbes 1964). This new usage of 'hyacinth' In Latin may have been based on their familiarity with the local *Hyacinthus orientalis*, a violet flower, which is native to the Phoenician hinterland, having the same hue as *Tekhelet*. Hyacinth Purple and Tyrian Purple (biblical *Argaman*) were produced from various species of shellfish. It may be noted that Pliny also lists 'scarlet' as the third dyed wool product of his time, thus paralleling the trio of biblical colours. The details of PlIny`s description of shellfish dyeing are remarkably similar to those of talmudic *Tekhelet*, including treatment of wool with fresh and clear extract and the test dyeing. Furthermore, no alternative process is recorded in antiquity for dyeing wool with shellfish.

Accordingly it could be concluded, with a high degree of confidence, that *Tekhelet* of the Bible and the Talmud is the Hyacinth Purple of the classical world (Ziderman 1981). This conclusion justified applying to *Tekhelet* all of the research findings regarding classical hyacinth.

In this paper, we will deal with three issues:

1. Semantics and etymology of colour designations
2. Identification of the particular shellfish species used in antiquity to dye *Tekhelet*
3. Resolving the anomalies and contradictions encountered in modern experimental studies of dyeing *Tekhelet*

Semantics and etymology of colour designations (Ziderman **1990a**)

Colour designations (e.g. blue, purple, and scarlet) may have one of three meanings:

- *aesthetic* - an abstract term for colour sensation or hue
- *chemical* - name of dyestuff substance
- *dyed textile*, such as fibres, yarn, cord, fabric or garment, that is a commercial commodity

Ancient references, biblical and talmudic, are to be understood in *this third sense*. Accordingly, identification of an ancient colour means identifying a commercial textile, rather than a particular shade. Colour terminology varies both within a language and through translation. Furthermore, there is a distinction between generic names and hue colour names. Let us discuss three cases – red, purple and blue.

Red

Biblical Hebrew *Tolaat Shani* is translated variously as 'scarlet' and 'crimson'. Which rendering is more appropriate?

In current usage, crimson (= carmine) is a bluish red tone, while scarlet is a red of orange tone. Crimson, running into the range of purples, is so wide as to be a generic term like red. In contrast, the colour range of scarlet is very narrow. Now this modern hue connotation of scarlet evidently originated in 17th century Europe with the introduction of tin, as stannous chloride, as a novel mordant for dyeing wool with American cochineal (Gerber 1978). The resulting dyeing was a brilliant scarlet that was named 'Dutch Fire' and 'Gobelin Scarlet' and it replaced the crimson dyeing previously obtained with alum mordant. Thus, the shade denoted 'scarlet' changed as a result of technological advance, and could no longer be appropriate for *Tolaat Shani*. Nevertheless, the name 'Venetian Scarlet' was still retained for kermes crimson mordanted with alum.

A second reason for preferring 'crimson' for *Tolaat Shani* depends on its etymology. 'Crimson' is derived from the word kermes, that designates 'worm': this is referring to the larvae of these scale insects that rapidly crawl over the leaves and branches of the host oak tree until they find a suitable place for permanent attachment. Now '*Tolaat*' here means 'worm' in this sense of larva, while '*Shani*' means 'reddish'.

Furthermore, the synonym for '*Tolaat Shani'* in later biblical Hebrew is '*Karmil*', which Is evidently of common etymology to 'kermes'. Interestingly, the colour 'vermilion' is derived from the same source as 'worm', and it denotes a warmer red than scarlet, i.e. it has a stronger yellow tone.

In the King James' Version, the rendering is 'scarlet', but that was in 1611, before the colour now called 'scarlet' was mordanted with tin. In current nomenclature, therefore, '*Tolaat Shani'* is correctly translated 'crimson'.

Purple

'Purple 'in English is not the name of a particular hue but a generic term describing a range of hues or a class of similar hues. 'Purple' is generic in three senses:

- *Coloristic*: Purple is the sensation of mixing spectral red and blue lights in various ratios: It is outside the spectrum. (By contrast, 'violet' in English is a spectral division and very limited in its range of hue. In German, however, 'violet' is a generic term, just as it is in the Hebrew *'Segol'* for violet.)
- *Tinctorial*: In Hyacinth Purple and Tyrian Purple, blue tone predominates in the former giving a bluish purple, but red tone in the latter giving a reddish purple. Since red predominates in *modern* 'purple', it is strictly sufficient to use 'violet' and 'purple' respectively for *Tekhelet* and *Argaman*.
- *Malacological:* It means dyeings with any species of shellfish, whatever the colour.

Blue

The King James` Version renders *Tekhelet* as 'blue'. In the Addendum, Tracey Rihll discusses the changing meaning of 'blue' since the 17th century. She shows that 'blue' was then a generic term that designated a range of hues and would have included reddish blue, i.e. violet. Unfortunately, this rendering has been retained in the Revised Standard Bible until this very day. "Violet" is indeed preferred for *Tekhelet* in several dictionaries and in modern translations of the Bible (The Jerusalem

Bible, London, 1966; New English Bible, Oxford, 1970; The New American Standard Bible). The colours that are obtained from the various shellfish, as detailed in the following section, confirm the validity of this translation as 'violet'.

Why Is *Tekhelet* rendered '*gelb*' (yellow) in Luther's Bible? He was translating from the Greek version 'hyacinth', which is also the name of a yellowish mineral!

The shellfish used in antiquity to dye *Tekhelet*

Remains of purple dyeing installations have been identified at many archaeological sites around the Mediterranean (Ziderman 1990b). The three species of shellfish found at the sites are, in order of their Importance, banded dye-murex (*Phyllonotus trunculus*), spiny dye-murex (*Bolinus brandaris*) and the rock-shell or dogwinkle (*Thais haemastoma*) (FIG. 1). They are all still extant.

The dogwinkle lives on rocks in the shallow inter-tidal zones, but could be collected by hand during low tide only in a very calm sea. It has a worldwide distribution.

Further out to sea, the banded dye-murex occupies depths down to 15 m, on stony coarse sands, and could be caught by divers or with baited baskets. This species is indigenous to the Mediterranean.

Spiny dye-murex is found on soft sea bottoms down to depths of 200 m and would require dredging nets for gathering. They are also widely distributed outside the Mediterranean.

Archaeological surveys of the shells found in dyeing sites (Reese 1987, 1980, 2000) show that banded dye-murex is usually accumulated *separately* from the other two species (FIG. 2). This finding has been explained as evidence for their use in separate dyeing processes, namely production of *Tekhelet* from banded murex and *Argaman* from spiny murex and dogwinkle (Herzog 1913). Furthermore, remains of banded dye-murex are found to be much more prevalent than the other species, indicating that their product was the main type of purple made.

In 1832, Bartolomeo Bizio (1791-1862), Professor of Pharmacy at the University of Venice, reported the first definitive experimental study of the dyestuffs that could be prepared from shellfish which he had collected from the local sea (Grimaud de Caux 1856; Grimaud de Caux and Gruby 1842; Bizio 1860). He discovered that banded murex yields a blue-purple (violet) and is thus the source of *Tekhelet*, Pliny's *conchylia*. His chemical analysis separated this violet as a mixture of the two pigments – indigo-blue and purple. Spiny murex and dogwinkle both gave a reddish purple and he accordingly ascribed them to be the source of *Argaman*. These two latter species are, respectively, the *pelagia*/*murex*, and *bucinum*/*purpura* cited by Pliny as the source of Tyrian purple in the *diphaba* two-vat process (Ziderman 1992). In chemical analysis, Bizio found their purples to be homogeneous and *identical* to the purple constituent of the banded murex dyeing.

Contradiction and controversy

However, 26 years later, Henri de Lacaze-Duthiers (1821-1901), a French zoologist, sailed out from Minorca to study animal life in the Mediterranean (Lacaze-Duthiers 1859). He saw a fisherman in the boat drawing yellowish designs on his shirt with the help of juice of a rock-shell he had broken open. The yellow colour soon turned a bright purple under the influence of the sun.

Lacaze-Duthiers immediately believe that ancient Tyrian Purple manufacture had been rediscovered, being unaware of Bizio's earlier results. In his hands, however, not only did dogwinkle and spiny dye-murex give reddish purple, but so did the banded murex! He insisted that the basic hue obtained from all the species was the same red-purple.

Subsequently, there developed a furious and unresolved controversy with Bizio over the colour produced from banded murex. Bizio defended the unique bluish constituent he obtained. But as he survived Bizio by 40 years, Lacaze-Duthiers managed to capture the field. Of course, Lacaze-Duthiers' account left no place for identification of *Tekhelet* or Hyacinth Purple! Eventually, his view became so popular that, for lack of any alternative hypothesis, it even engendered a speculation that *Tekhelet* be the transient turquoise colour observed during formation of purple (Feliks 1962, 1981).

Later experimental studies of the shellfish species by eminent chemists (Friedlander 1922; Pfister 1937, p.11; Bouchilloux and Roche 1954; Fouquet and Bielig 1971; Elsner 1992) all confirmed Bizio's findings, which were also endorsed by Dedekind (1898) and Herzog (1987).

The purple constituent is identified chemically as 6,6`-dibromoindigotin (DBI) . However, it could still have been argued that the indigo-blue constituent of banded murex-dye be an *artefact* formed by inadvertent debromination of DBI during processing. This concern was dismissed when Fouquet and Bielig (1971) published a definitive investigation of the biochemistry of shellfish dyestuffs and their natural precursors. They found that hypobranchial glands of banded dye-murex contain two soluble, colourless dye precursors, indoxyl and bromo-indoxyl. Two molecules of indoxyl react chemically to form indigo-blue. Two molecules of bromo-indoxyl react chemically to form DBI.

On the basis of this further decisive evidence, it was concluded (Ziderman 1981, 1986b, 1987a and 1987b) that *Tekhelet* was manufactured in antiquity from banded dye-murex. It had a violet colour and its chemical composition is essentially a mixture of indigotin and DBI.

The conclusion that ancient *Tekhelet* was a violet-blue colour has been corroborated by ancient texts. A seventh-century document recently discovered (Granger-Taylor 2001) describes imitation of *Tekhelet* by a double dyeing with woad and madder, which is also the chemical composition reported in a new analysis (Koren 2001a) of the violet wool tassel from the Cave of the Letters (Yadin 1963). This composition corresponds to a literal meaning of the Talmudic description (Midrash *Sifrey*, on Numbers

14:41) of forging ritual *Tekhelet:* 'Behold I use red dye *and* indigo so that they resemble *Tekhelet:* who then could expose me?'

Further support for assigning the above composition to *Tekhelet* is provided by the chemical analyses reported (cited in Ziderman 1990b) for five archaeological textiles as being dyed with both DBI and indigotin. Wouters (1992) characterised as 'a *Ph. trunculus*-type' a textile from a Sarmathian tomb of the first century BCE on the Black Sea coast, in accordance with its analytical data, namely indigotin (70%), DBI (7%) and 6-monobromoindigotin (MBI, 23%; see later discussion).

No trace of brominated derivatives have been detected in chromatographic analysis of indigotin-dyed archaeological textiles (Koren 2001b). This should be considered as proof that the dyestuffs were obtained from a vegetable source (indigo or woad) and not from shellfish. Accordingly, banded dye-murex would not have been a source for dyeing indigotin blue, via decomposition of MBI. Furthermore, such a use is untenable, considering the ready availability of inexpensive woad and/or indigo, used in the ancient Mediterranean world for producing an *identical* product. It may be concluded that chemically the dyestuff of ancient *Tekhelet* from shellfish was not purely indigotin.

After publishing my conclusions (Ziderman 1981), I was informed by marine ecologist Ehud Spanier of Haifa University, that the banded dye-murex he had gathered in Israel gave a red-purple dye of the *same colour* as he obtained from spiny murex and dogwinkle. This had been the contention of Lacaze-Duthiers!

At my request, he supplied me with live shellfish. Following the procedure of Fouquet and Bielig (1971), I obtained in my laboratory the same result as had Bizio, a violet from banded murex and purples from spiny murex and dogwinkle (Ziderman 1986c) .

Resolving the anomalies and contradictions encountered in studies of dyeing *Tekhelet*

How can these contradictions between the experimentalists be resolved?

Now it was recently observed that, on exposure to steam, wool dyed red-purple with banded dye-murex *changes colour to blue*. This must be the result of debromination of the purple constituent to leave only indigo-blue. But DBI is too stable chemically to undergo this chemical reaction in such mild conditions! Therefore, I proposed the following hypothesis in order to resolve this anomaly (Ziderman 2001).

Firstly, Elsner (1992) had discovered gender differentiation among banded dye-murex snails: males furnish largely indigo-blue dye and the females purple dye (DBI) (*cf.* Ziderman 1992). In other words, indoxyl precursor is accumulated in the males' hypobranchial glands and bromo-indoxyl largely in the females`.

Secondly, during 1991-1995, several laboratories (Wouters and Verhecken 1991; Michel *et al*. 1992; Koren 1995) detected the presence of MBI in banded murex dyeings, as a third constituent in admixture with DBI and indigotin. It should be noted that MBI had still never been synthesised or isolated in a pure form.

Now DBI can be formed when the female glands' bromo-indoxyl is able to react alone. Indigo-blue can be formed only if the male glands' indoxyl is able to react alone. Premature admixture of precursors indoxyl with bromo-indoxyl will permit their reaction with each other to form MBI. ThIs could explain the different colours reported respectively by Lacaze-Duthiers and Bizio a century and a half ago. Furthermore, the hypothesis was that purple-coloured MBI, being an asymmetrical molecule, be unstable enough to *readily* lose its bromine substituent to form indigo-blue: this would account for the colour change of purple wool dyed with banded murex and also for associated experimental anomalies. Fortuitously, at the same meeting, the first chemical synthesis of MBI was reported (Cooksey 2001). He kindly provided me with wool samples that he had dyed with his synthetic MBI.

Successful performance of the experiment to prove my hypothesis is hereby reported. On gentle heating in water, the violet-coloured wool dyed with MBI readily changed colour to blue. The experiment was repeated in a demonstration before the Meeting plenum.

DBI is an eminently stable material. If so, how could it have been used to dye wool as *Tekhelet* and *Argaman* in antiquity? The powerful chemical reducing reagent hydrosulphite, required in modern industry for dyeing (jeans) with synthetic indigo-blue was, of course, not available then. My late colleague, Prof. Otto Elsner of Israel was able to perform these dyeings by utilising the natural reducing property of the wool being dyed to solublize the DBI in the vat for dyeing (Elsner 1992).

Conclusions

Tekhelet was manufactured in antiquity from banded dye-murex (*Ph. trunculus*). It had a violet colour and its chemical composition is a mixture of indigo-blue and DBI.

When the hypobranchial gland contents of male and female banded dye-murex are mixed before all precursors present have formed DBI and indigo-blue, MBI may be formed. The content of the indigo-blue constituent is thereby lowered. If sufficient MBI is thus produced, the dyeing will not be violet but purple. This explains the observation reported by both Lacaze-Duthiers (1859) and Spanier (personal communication).

The author's hypothesis that MBI is unstable, being converted into blue indigotin by a debromination, is experimentally verified. ThIs novel chemical reaction provides the rationalisation for hitherto unexplained anomalies reported by many authors who prepared purple dyes from banded murex.

Renewed chemical research is required to find experimental conditions that will minimise formation of MBI during *Tekhelet* manufacture, in order to obtain a more definitive violet hue.

Addendum

Dear Dr Ziderman,

Re: the changing meaning of 'blue' in English.

MacAdams' arguments you already know I believe. Apart from the OED, which has a fairly subscribed listing with dates of the terms of reference for blue in past usage, you could look at e.g. a Dictionary of English Dialects, where you will find it was used in the 1800s for example to describe a pony, a pig, cows, milk, flint, a number of diseases in animals (e.g. 'blue-spald' in cattle), of numerous plants some of which we think of as blue but many others as green (e.g. ground ivy, marsh grass), of a lot of birds which we would call grey, brown or black (e.g. hedge sparrow, black tern, pigeon).

It is also worth noticing, on the symbolic front, that it had and still has negative connotations in English: in Shakespeare's time it was the colour of servants' clothes and could be used as shorthand to refer to someone of low standing; a 'blue gown' in Scotland was a licensed beggar; a blue-belly was a Protestant dissenter; a blue day was one on which something bad had taken place (opposite to 'red letter' day); we still of talk of 'being blue' to mean melancholy. Given its socio-economic and symbolic focus, I cannot imagine that people had in mind either azure-type hues or expensive dyes. The change over to meaning blue-blue (i.e. not red-blue, green-blue, blue-black, blue-grey, blue-brown) seems to start in the C18 (and takes longer to penetrate dialectical usage), after Newton anyway, and at the same time the range of the meaning of violet and indigo started shrinking - they have practically disappeared in modern English. So when Newton (or anyone before him speaking English) said 'blue', he did not mean what we now assume the word to mean.

Sorry I couldn't help with hyacinth - I don't remember it ever coming up in Aristotle, and Eleanor Irwin's paper [this volume] seemed to confirm that.

Best wishes

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References

Bizio, B., 1860. 'Reclamation' *Cosmos* 16: 624.

Born, W., 1937. *Purple*. Ciba Review 4.

Bouchilloux, S. and J. Roche 1954. 'Sur les prochromogenes et les pigments purpuriques de Murex trunculus Linne' *Comptes rendus des sciences, societie de biologie* 148: 1732-34.

Cooksey, C., 2001. 'The synthesis and properties of 6-bromoindigo: indigo blue or Tyrian purple? The effect of physical state on the colours of indigo and bromoindigos' *Dyes in history and archaeology* 16/17: 97-104.

Dedekind, A., 1898. 'La pourpre verte et sa valeur pour l`intepretation des ecrits des ancients' *Archives de Zoologie Experimentale et Genera le* (3rd series) 6: 467-80.

Edelstein, S. M., 1987. 'Preface' in E. Spanier (ed.) *The Royal Purple and the Biblical Blue*: 11-13. Jerusalem: Keter.

Elsner. O., 1992. 'Solution of the enigmas of dyeing Tyrian purple and the biblical *tekhelet' Dyes in history and archaeology* 10:11-16.

Feliks, J., 1962. *The animal world of the Bible*. Tel Aviv.

Feliks, J., 1981. *Nature and man in the Bible*. London.

Forbes, R. J., 1964. *Studies in ancient technology* 4: 98-142. Leiden: Brill.

Fouquet, H. and H.-J. Bielig 1971. 'Biological precursors and genesis of Tyrian purple' *Angewandte chemie international edition* 10: 816-17.

Friedlander, P., 1922. 'Uber die farbstoff aus Purpura aperta und Purpura lapillus' *Berichte der deutschen chemischen gesellschaft* 55: 1655-8.

Gerber, F. G., 1978. *Cochineal and the insect dyes*. Ormond Beach: Gerber.

Granger-Taylor, H. 2001. 'Dyes and coloured textiles of the Greek and Roman world' *This volume.*

Grimaud de Caux, G., 1856. 'Sur l`animal de la pourpres anciens' *Revue zoologique* 8: 34-42.

Grimaud de Caux, G. and A. Gruby, 1842. 'Description anatomique de l`organ qui fournit la liqueur purpurigene dans le Murex brandaris, et analyse microscopique de cette liqueur' *Comptes rendus hebdomadaires des seances de l`academie des sciences* 15: 1007-9.

Herzog, I., 1987. 'Hebrew Porphyrology' (D. Litt. dissertation, University of London, 1913) in E. Spanier (ed.) *The Royal Purple and the Biblical Blue*: 17-131. Jerusalem: Keter.

Koren, Z. C., 1995. ''High-performance liquid chromatographic analysis of an ancient Tyrian purple dyeing vat from Israel' *Israel journal of chemistry* 35: 117-24.

Koren, Z. C., 2001a. 'The fashionable colours of ancient Israel' *This volume.*

Koren, Z. C., 2001b. Personal communication.

Lacaze-Duthiers, H. de, 1859. 'Memoire sur la pourpre' *Annales des sciences naturelles: zoologie* (4th series) 12: 5-84.

Michel, R. H., J. Lazar and P. E. McGovern, 1992. 'The chemical composition of the indigoid dyes derived from the hypobranchial glandular secretions of murex molluscs' *Journal of the society of dyers and colorists* 108: 145-50.

Pfister, R., 1937. *Nouveaux textiles de Palmyre.* Paris: Editions d`art et d`histoire.

Reese, D. S., 1987. 'Palaikastro shells and Bronze Age purple-dye production in the Mediterranean basin' *The annual of the British school of archaeology at Athens* 82: 201-6.

Reese, D. S., 1980. 'Industrial exploitation of murex shells: purple-dye and lime production at Sidi Khrebish, Benghazi' *Libyan studies: the society for Libyan studies 11th annual report (1979-80)*:79-83.

Reese, D. S., 2000. 'Iron age shell purple-dye production in the Aegean' in J. W. Shaw and M. C. Shaw (ed.) *Kommos 14. The Greek sanctuary* part 1: 643-47. Princeton: University Press.

Wouters, J., 1992. 'A new method for the analysis of blue and purple dyes in textiles' *Dyes in history and archaeology* 10: 17-21.

Wouters, J. and A. Verhecken 1991. 'High-performance liquid chromatography of blue and purple indigoid natural dyes' *Journal of the society of dyers and colorists* 107:266-9.

Yadin, Y., 1963. *Findings from the Days of Bar-Kokhba in the Cave of the Letters*. Jerusalem: Bialik (Hebrew).

Ziderman, I. I., 1981. 'Blue thread of the Tzitzit: Was the ancient dye a Prussian blue or Tyrian purple' *Journal of the society of dyers and colorists* 97: 362-4

Ziderman, I. I., 1986a. 'Biblical dyes of animal origin' *Chemistry in Britain* 22: 419-21, 454 and 638.

Ziderman, I. I., 1986b. 'Purple dyes made from shellfish in antiquity' *Review of progress in coloration & related topics* 16: 46-52.

Ziderman, I. I., 1986c. '3600 Years of purple-shell dyeing: characterisation of hyacinthine purple (*tekhelet)' Advances in chemistry series* 212: 187-198.

Ziderman, I. I., 1987a. 'Halakhic aspects of reviving the ritual tekhelet dye in the light of modern scientific discoveries' in E. Spanier (ed.) *The Royal Purple and the Biblical Blue*: 207-20. Jerusalem: Keter.

Ziderman, I. I., 1987b. 'First identification of authentic Tekhelet' *Bulletin of the American schools of oriental research* 265: 25-33

Ziderman, I. I., 1990a. 'Textile dyes of animal origin in ancient Israel and Phoenicia' *International workshop on history of chemical technology*. Jerusalem: Hebrew University (not published).

Ziderman, I. I., 1990b. 'Seashells and ancient purple dyeing' *Biblical archaeologist* 52:98-101.

Ziderman, I. I., 1992. 'Molluscal source of biblical "blue" dyestuff'. *Proceedings of the 9th international malacology congress (Edinburgh 1986)*: 407-14.

Ziderman, I. I., 2001. 'Revival of biblical *tekhelet* dyeing with banded dye-murex (*Phyllonotus trunculus*): chemical anomalies' *Dyes in history and archaeology* 16/17: xvii and 87-90.

Captions

Fig. 1

These three species of marine snails were used in antiquity for manufacturing purple dyes. The shells are, left to right, banded dye-murex (*Phyllonotus trunculus*), used for dyeing *Tekhelet* hyacinth purple, and spiny dye-murex (*Bolinus brandaris*) and dogwinkle (*Thais haemastoma*), both used for dyeing *Argaman* Tyrian purple. The dogwinkle shell bears signs of marine wear and encrustation of biological fouling.

Fig. 2

The shell pictured at left is banded dye-murex (*Phyllotonus trunculus*), the species used in antiquity to dye bluish purple (*hyacinth* in Greek; *tekhelet* in biblical Hebrew). This shell has blunt spikes arranged in a spiral band and a broad channelled beak.. Pictured on right is a fragment of the same species with the spire smashed off to expose the hypobranchial gland for excision and dye production: this was found at the Appolonia site in Israel on a 2nd century-stratum.